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M149A2/PINTLE MOTION BASE SIMULATOR VALIDATION FINAL REPORT

JULY 1994

By

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13. ABSTRACT *(Maximum 200 words)*

This report presents the results of the validation of the Pintle Motion Base Simulator (PMBS) using the M149A2 400-gallon Water Trailer as a test specimen. It describes the execution and results of 4 different tests on the M149A2 trailer and of a DADS model of the trailer. It also compares the results of these different tests to determine and quantify the accuracy of the simulations run on the PMBS when using either proving ground data or DADS data as input.

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PREFACE

This report presents the validation work done on the Pintle Motion Base Simulator (PMBS) using the M149A2 Water Trailer as the test specimen on which this validation was performed. Questions regarding the testing of lunette trailers on the Pintle Motion Base Simulator are to be referred to the U.S. Army Tank-Automotive Research, Development, and Engineering Center, ATTN: System Simulation and Technology Division, AMSTA-RYA, Warren, MI 48397-500, Telephone: AUTOVON/DSN 786-6228, Commercial (810)574-6228, FAX (810)574-8667.

This validation work was primarily performed during the period of February 1994 to March 1994.

Many parties played an important role in the many facets of this validation work some of whom include: Aleksander Kurec for his help in the Mechanical and hydraulic portions of the work, Mike Pozolo for his work running the many DADS models of the M149 trailer, Dr. Beck for his expertise and knowledge in the area of systems, all of the technicians in the Simulation Function Branch, their support throughout the duration of this work was invaluable, and all of the Engineers and Technicians of MTS Systems corporation who spent many hours designing, building, trouble shooting, and tuning the simulator.

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1.0 INTRODUCTION

1.1 Background

Recent financial cuts in the Defense Department have dictated that Army vehicle program managers and testers seek out more efficient methods to reduce the time and costs of vehicle development. Some typical vehicle evaluation processes are time-inefficient and consequently costly. These traditional test methods concentrate on extensive proving ground testing for system validation and accreditation.

1.1.1 TACOM/TECOM Agreement

To respond to this situation, analytical and physical (motion base) simulation methods and techniques are offered at the Tank-Automotive Research Development and Engineering Center (TARDEC) at the U.S. Army Tank-Automotive Command (TACOM) as a cost-effective compliment to proving ground testing. To achieve this, the commanders of TACOM and the U.S. Army Test and Evaluation Command (TECOM) established an initiative and agreement to explore the effectiveness of motion base simulation and to determine how it could augment proving ground testing. (Reference memo, TACOM, Commander, August 22, 1991, and memo, TECOM, Commander, October 31, 1991). These memoranda are included in Appendix K.

1.1.2 Candidate Trailer

To carry out this endeavor, representatives of the Combat Systems Test Activity (CSTA) of TECOM and the Directorate for Product Assurance and Test, the Trailer Management Office, and the System Simulation and Technology Division of TARDEC, met to plan and carry out a validation process for trailer simulator testing. Trailers were selected for two reasons; (1) they are ideal test candidates for motion simulator usage, as they require no power train and (2) the Trailer Management Office funded the majority of the simulation development costs. An M832 dolly set and shelter, scheduled to undergo a Product Qualification Test (PQT) in late 1991, was selected to be the candidate system with which to compare and assess proving ground events to laboratory events.

However, several vehicle problems and project delays were encountered with the M832 PQT. Since the key technical objective in the simulation laboratory is to reproduce proving ground vehicle responses (hence simulating the dynamic environment), another, more proven trailer design was selected to be the candidate - the M149A2 single-axle 400-gallon water trailer.

This report presents our validation work, results, and recommendations for single-axle trailer testing. It contains a presentation and analysis of very detailed trailer response characteristics using the high-fidelity Pintle Motion Base Simulator (PMBS). Two methods of determining the simulator drive commands are presented and discussed.

Plans have been made for the summer of 1994 to pursue a similar effort using the original candidate - the M832 5-1/2-ton four-wheeled dolly set. Completion of this work will then provide substantial technical validation data for two significantly different classes of trailers.

1.2 Pintle Motion Base Simulator.

Engineers and technicians from the Physical Simulation Laboratory (PSL) completed installation and check-out of the Pintle Motion Base Simulator (PMBS) in October 1993. The PMBS consists of electronics, software, and fixturing which provide the addition of lateral, longitudinal, and vertical force inputs to the trailer lunette in order to simulate the interaction dynamics between the trailer and its prime mover. A methodology was developed and Remote Parameter Control (RPC™) software has been procured which generate simulator drive commands that reproduce known (desired) responses (remote parameters) in the lab. The design is based on the typical motions of trailers with a gross vehicle weight (GVW) of up to 20,000 pounds. MTS Systems of Minneapolis, Minnesota designed the simulator and provided the electronics, software, and fixturing. Figure 1-1 shows the mechanical configuration of the PMBS.

Forces are applied to the specimen via a bellcrank and strut arrangement. A clamping fixture couples the lunette directly to the simulator. The trailer specimen's tires rest directly on platens which are attached to hydraulic actuators. A hydraulic distribution system supplies cool, clean and controlled hydraulic fluid under pressure to power the actuators.

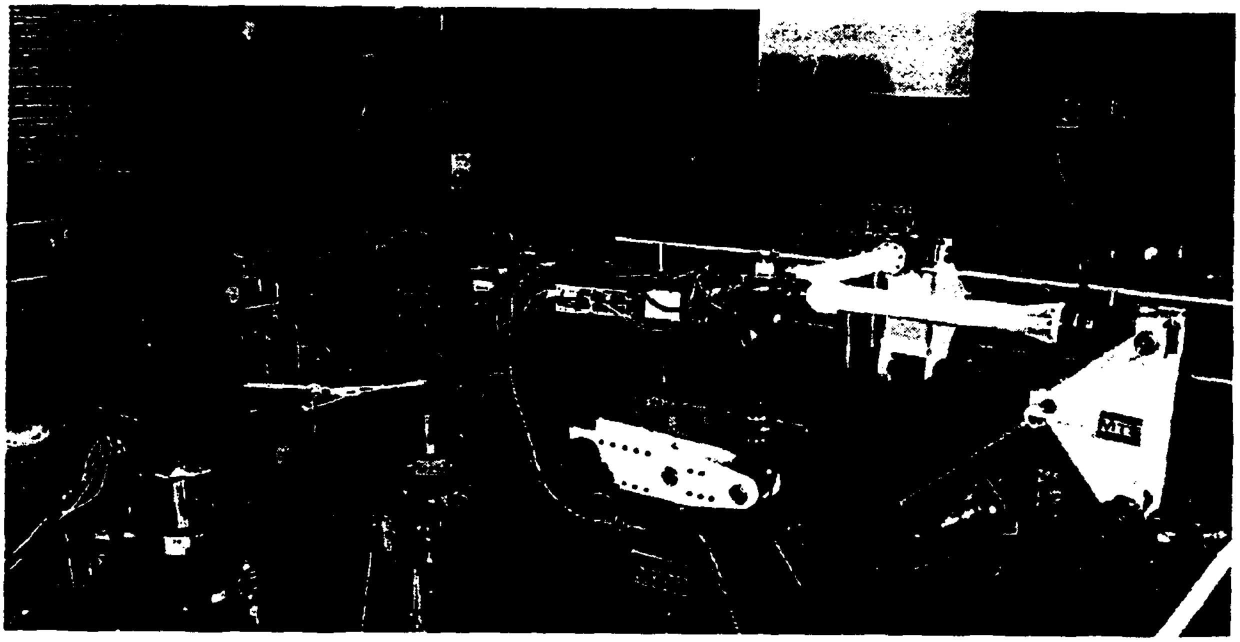

Figure 1-1. PMBS with M149A2 Trailer attached.

Figure 1-2 shows the PMBS control system configuration. A system of analog and digital electronics packaged in modular form performs the operation, control and status monitoring. This microprocessor-based system provides the operating functions of the PMBS such as hydraulic power supply control, emergency stop, and system interlock detection programming. Analog controllers provide for the closed loop control of the actuators, transducer conditioning, and some interlock monitoring functions as well.

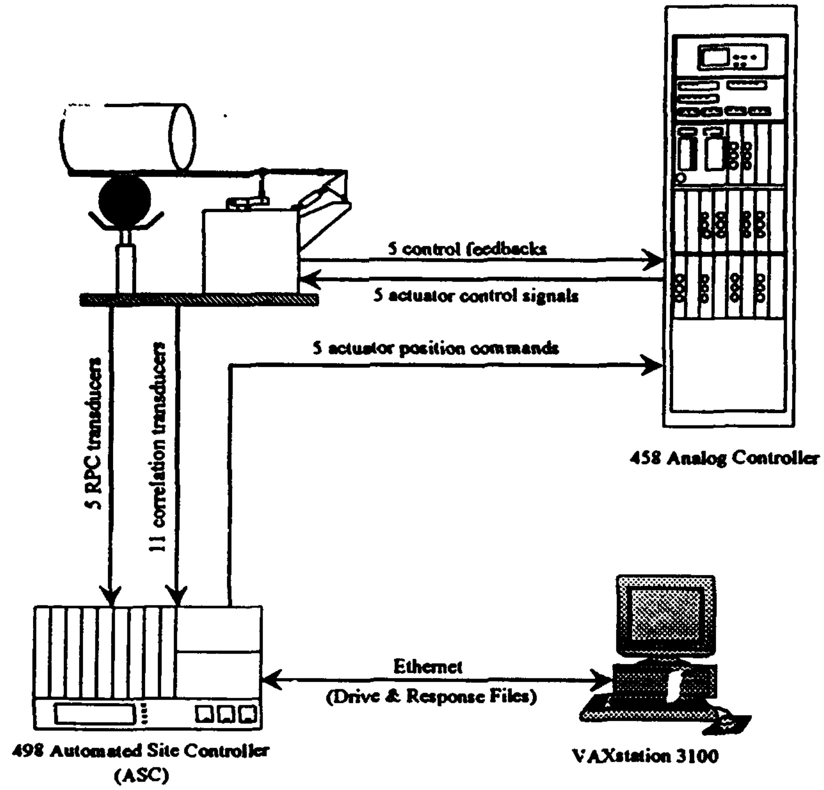

Figure 1-2. PMBS/M149A2 System.

The digital system consists of a Digital Equipment Corporation VAX™ workstation, real-time controller, ethernet local area network, and MTS Systems' proprietary RPC™ III software. The RPC™ testing technique allows the near exact replication of displacement, acceleration, strain, or force at a vehicle location remote from the excitation source. The RPC™ III software accounts for nonlinearity effects and response characteristics of the simulator, specimen, and electronics. To do this, a frequency response function (FRF) of the entire PMBS/trailer system is calculated. An estimate of the drive command is made by convolving the inverted FRF with the desired response signal. Since the system is nonlinear, several iterations of this process are required to reduce the error between the actual and desired response.

The system is designed such that, once a drive command is generated, it can be downloaded to the real-time controller which can output drive signals and record simulator and specimen response data. This frees the VAX™ workstation for data processing and analysis by the test engineer.

This high-fidelity simulator was particularly necessary because of limitations in the design and signal generation method of the previous simulator (fixed lunette) shown in Figure 1-3.

The old fixed-lunette simulator consisted of two actuators (one per tire location) which provide vertical motion into the tires. The actuators were driven with signals which represented a profiled (known height versus distance) terrain at a selected speed. Although useful for testing

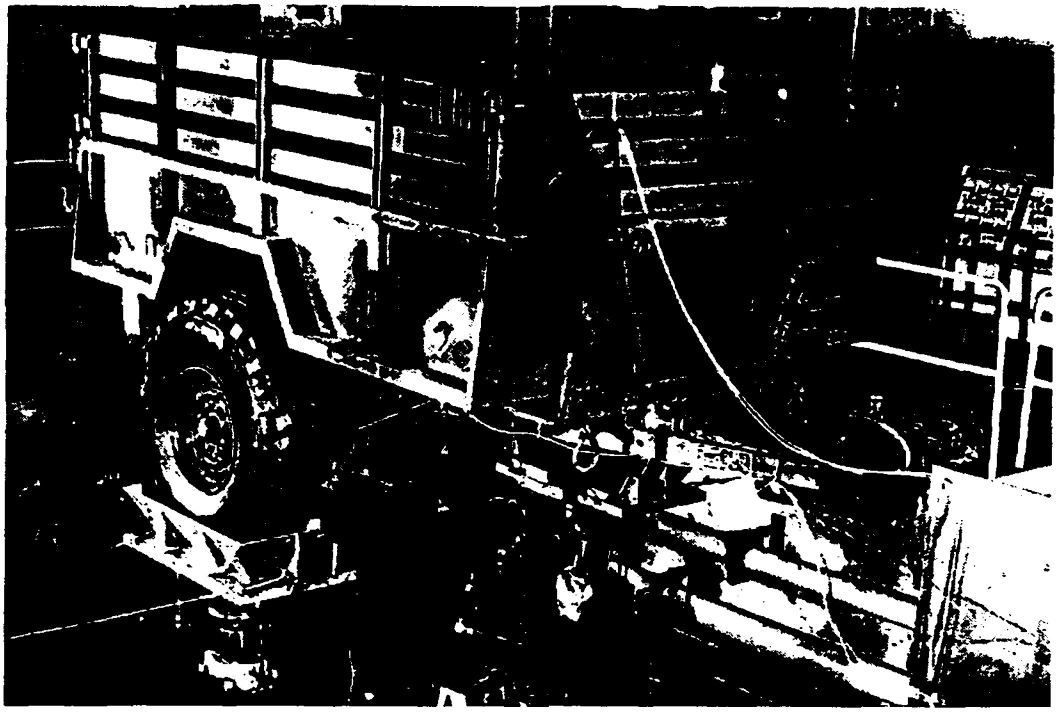

Figure 1-3 M101 Trailer on the Fixed Lunette Motion Base Simulator

some vehicle parameters, its control system and fixturing limited its capabilities. This simulator needed improvement because:

- The terrain signal, when input through the actuator to the tire, would generally result in higher trailer dynamics than experienced at the proving ground.
- The actuators only produce vertical motions at the tire/spindle and neglected considerable shock and vibration at the lunette.
- Fixture and electronic cross-coupling was difficult to measure or eliminate.
- Servo-hydraulic system response, although optimized, was limited.

1.3 PMBS Specifications

System-level specifications for the PMBS were carefully developed using a combination of computer-based dynamics modeling and simulation, and data acquired from the proving ground. The final design of the PMBS met all major specifications and goals of the original purpose, which was to accurately test all lunette-type trailers of GVW up to 20,000 pounds.

1.4 PMBS Benefits

The acquisition of the PMBS will reduce the time required for the vehicle development process and analysis. The PMBS, being a high-fidelity, multiaxial simulator, can provide experimental test loading conditions for finite element analysis of trailer and automotive components. The PMBS will also reduce the time required to conduct a structural durability test cycle. A methodology is currently being developed to edit out all nondamaging events. This method will allow the simulator to reproduce only the damaging events experienced at the proving ground in a much shorter time. The automobile industry has noted a reduction in test time of 75 percent.

Laboratory testing of vehicles has several advantages over proving ground testing. Laboratory motion simulators offer repeatability of dynamic events, since the simulator drive commands are controlled by a computer. Also, weather influences, driver variability, and course maintenance introduce variables at the proving grounds which make it difficult for the vehicle designer to isolate the cause of performance differences among different vehicle modifications.

Vehicle designers and Program Managers need assurance of the performance and reliability of their systems before they are sent to the proving ground for extensive testing. Very high costs are incurred when vehicle systems fail proving ground tests, since these typically require extensive personnel, logistics, and facility equipment. The PMBS should be used to quickly test trailer system changes before extensive proving ground testing.

2.0 OBJECTIVES

The objectives of this work were twofold; (1) to determine the performance of the PMBS and its ability to reproduce actual service-life conditions, and (2) to gain acceptance of the motion base simulation method by the test and evaluation (T & E) community.

The performance of the PMBS has been quantified and an acceptance test was performed by TARDEC engineers and technicians with the assistance of MTS Systems Corporation. The results presented in Section 3.0 and in Table 5-1 indicate conformity to the contract specification.

This report contains statistical and graphical information which quantifies the ability of the PMBS and the associated simulation methodology to reproduce proving ground and service-life response data. The data are compared to proving ground-collected data. T & E community analysts and assessors now have the information necessary to determine the usefulness of the PMBS and how it can be used in their future test programs. The data can also be used in future tactical vehicle simulators for trucks, since the required fixturing and control system methodology share many similarities with that of trailers.

3.0 RESULTS AND CONCLUSIONS

The data produced and presented in this report clearly show that the PMBS and RPC™ method greatly improve the fidelity of simulation testing of trailers. The bandwidth of the PSL's trailer simulator has been increased by a factor of 4, from 10 Hz to 40 Hz. Acceleration is used as the control parameter for all of the control channels except for the longitudinal lunette, which uses strain. Acceleration was found to be a suitable parameter of control for inertially reacted mass.

Extensive testing and analysis, however, proved that strain is a far better control parameter in the longitudinal direction at the lunette. The error rate between desired and simulator response data averages only 6 percent.

How accurate does one need to be in matching simulation data with proving ground data? Do the proving ground tests always match the user's service-life conditions? These are difficult questions which are very important in any testing situation. Since fatigue failure is still a phenomenon not fully understood, controlled testing in a laboratory may be more effective than in the actual service environment.

No failures or problems arose during any of the tests which were done on the M149A2 trailer. None of the tests, however, were intended to evaluate the durability of the trailer, so failures were not expected. Accumulated mileage data were not recorded, but the total mileage is probably less than 100 miles for all tests.

In addition to these benefits, the PMBS, as a whole, increased our ability to test lunette trailers. It adds the ability to move the hitch of the tested trailer as it would move at the proving ground. It will be shown that the stresses and strains experienced at the proving ground can be reproduced accurately within the bandwidth of control. Also, the spindle control bandwidth has been greatly improved. Spindle accelerations can be accurately reproduced out to 60 Hz, whereas 10 - 12 Hz was the limit with the fixed-lunette test method. This method of testing also allows the engineer to use the output from a Dynamic Analysis and Design System (DADS) model as input to the control process. Although this method is not perfected yet, work is underway to improve the accuracy of the DADS modeling techniques so that the DADS outputs are accurate enough to be substituted for proving ground data. Our goal is to accurately implement and execute physical simulations on the PMBS with the RPC™ control techniques using only computer-based inputs.

The following conclusions can be drawn from the above results:

- Duty cycle reproduction has been dramatically improved over the old (fixed-lunette) method.
- The PMBS is appropriate for many applications such as:
  - "old" vs. "new" comparisons.
  - Contractor down-selections
  - Component failure reproduction.
- Lunette strains correlate in the frequency range of 0.6 to 40 Hz.
- Spindle accelerations correlate in the frequency range of 0.6 to 60 Hz.
- The current DADS-derived control generation method results in somewhat higher than realistic spindle acceleration and lunette strain.
- A flexible-body DADS model with lunette/pintle model would improve correlation.

4.0 RECOMMENDATIONS

4.1 M832 Dolly Set

Several recommendations to continue the work effort are presented here. The results presented in this report indicate marked improvements in fidelity with regards to simulation testing of light single-axle lunette trailers. A logical continuation of the work is to conduct a validation program on heavier trailer systems. One such system is recommended - the 5-1/2-ton M832 dolly set and shelter system. It is an ideal candidate because a workable proving ground data set exists with which to correlate lab results. This work is currently scheduled to occur in the TARDEC PSL in 1994.

4.2 Structural Analysis

The M149A2 trailer proving ground data collection exercises included only two channels of strain. These were axial and bending strain just aft of the lunette. No structural damage was noted at the proving ground or the PSL during this work. If additional strain data were available, estimates for fatigue life and potential damage assessment could have been made which are important for structural assessments. The downside to this request for additional channels is that it creates a burden for instrumentation engineers and is more costly. Additional strain gages will be considered for future proving ground and laboratory trailer validation tests.

4.3 Dynamics Model

There are limitations to the use of the DADS method for the prediction of desired forces for the PMBS. This limitation can clearly be seen in Section 5.3.5. This is primarily because DADS is a rigid-body methodology. However, there is work ongoing in the area of flexible body dynamics which will model the structural characteristics of the trailer. Further development and refinement of flexible-body dynamics and its applications in trailer/prime mover interaction will provide the physical simulation engineers with more accurate drive command determinations for the testing of trailers using analytically generated responses. Accurate acceleration, force, and strain predictions from these analytical models would alleviate some of the proving ground testing burden and expense, while providing a suitable desired data set in the event that proving ground testing is not possible or feasible.

4.4 Test & Evaluation Acceptance

It is recommended that the Army Test and Evaluation community consider the new simulation test methodology presented in this report. This method and test fixture provide a good starting point for serious consideration of using simulation to augment proving ground testing in reducing test costs while providing the Army with better-designed, more-durable trailers.

4.5 Other Applications

The multiaxial test fixtures along with RPC™ can also be applied to light- and medium-duty trucks. Tactical vehicle managers would also enjoy the savings and reliability that this simulation method offers.

4.6 Instrumentation Considerations

Some of the difficulties encountered when running the simulator tests and developing the method resulted from the instrumentation choices made for the proving ground test. After using the proving ground data to control the simulator for the first time, it could be seen that the instrumentation and respective locations could have been chosen better. Some of the necessary improvements include:

- Placement of accelerometers on the lunette even closer to the attachment point, possibly even on the ring of the lunette itself.
- Notch the lunette and other strain-gaged areas for better signal levels.
- Use more strain gages for correlation channels instead of accelerometers.
- Acquire linear displacement transducers which are similar to Aberdeen Proving Ground's (APG) linear potentiometers.

5.0 DISCUSSION/TESTING

5.1 General

The PMBS validation effort was actually a series of tests done on the M149A2 Water Trailer. These tests was done (as stated earlier) for two reasons:

(1) to determine the accuracy of each test with respect to proving ground results and,
(2) to provide the test and evaluation community with simulation results.

This section describes the pintle motion base simulator and its theoretical operation. It also describes the setup, execution, data, and analysis of each test of the M149A2 Water Trailer. A comparison of PMBS results to proving ground results is presented.

5.2 Motion Simulator

5.2.1 General

The fixed-lunette testing method, which utilized only tire coupled inputs, could not impart forces at the lunette in a controlled manner. The PMBS, however, adds three full degrees of freedom (DOF) to the lunette of an attached trailer, where there had been none previously. This simulator, therefore, is a five-DOF simulator and was designed to impart the correct motions and forces into the lunette of a trailer. The PMBS essentially consists of four separate components,

(1) Simulator Hardware (Fixturing, actuators, hoses, manifolds)
(2) 458 MicroConsole™ Analog Controllers (Proportional-Integral-Derivative (PID) control)
(3) 498 Automated Site Controller™ (ASC)
(4) 3100 VAXstation™ M76.

Each of these individual components is shown in relation to the others in Figure 5-1.

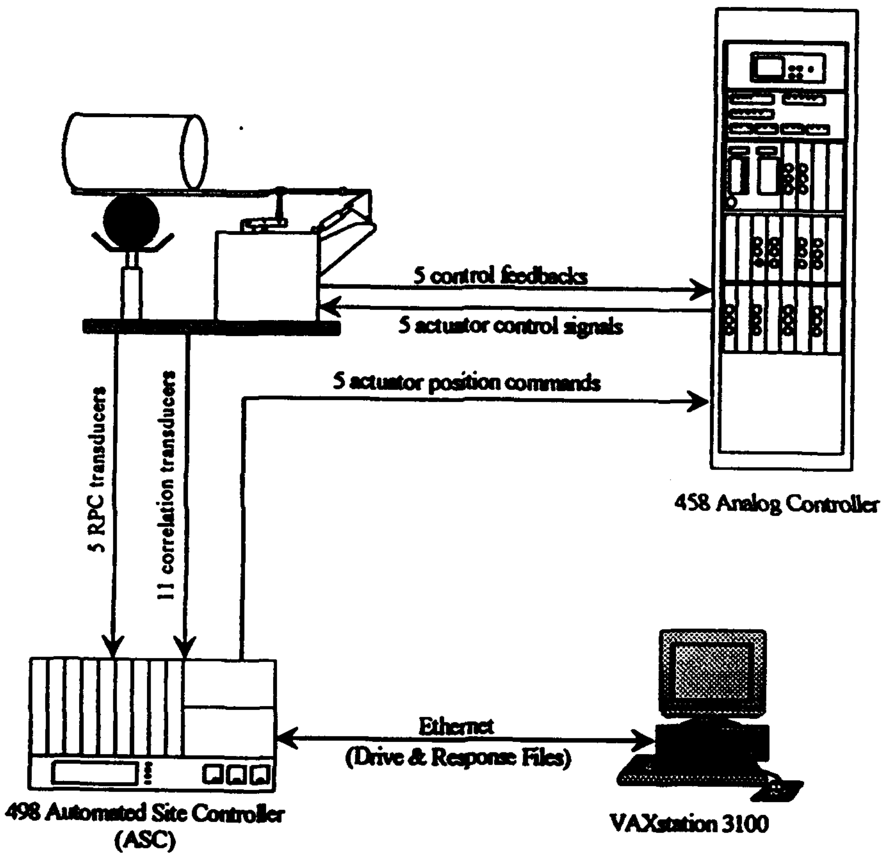

Figure 5-1. PMBS Test System.

5.2.2 Pintle Motion Base Simulator Hardware

The simulator hardware can be seen in Figure 5-2. Two fixture stands support the longitudinal, vertical, and lateral inputs. A tire-coupled actuator supports each tire. The lunette of the trailer is attached to the simulator via the clamping device shown in Figure 5-3. This fixture uses approximately 200,000 pounds of force and a soft metal crush washer to hold the lunette firmly in place and eliminates any slop between the lunette and the simulator. Forces and motions are imparted into the lunette via friction in the longitudinal and lateral directions and through direct mechanical coupling in the vertical direction. The three orthogonal struts which act on the lunette are each moved by actuators coupled through bell cranks. Bell cranks are used to limit the physical size of the simulator as all of the bell crank ratios serve to trade force at the lunette for displacement at the lunette. The position and force limits of each orthogonal direction on the simulator are given in Table 5-1. Each strut contains a load cell which provides the ability to control and/or monitor the load on each strut. The simulator is capable of two methods of control (1) position control at the actuator or (2) force control at the strut/load cell. Both of these methods of control are implemented by the 458 MicroConsole™.

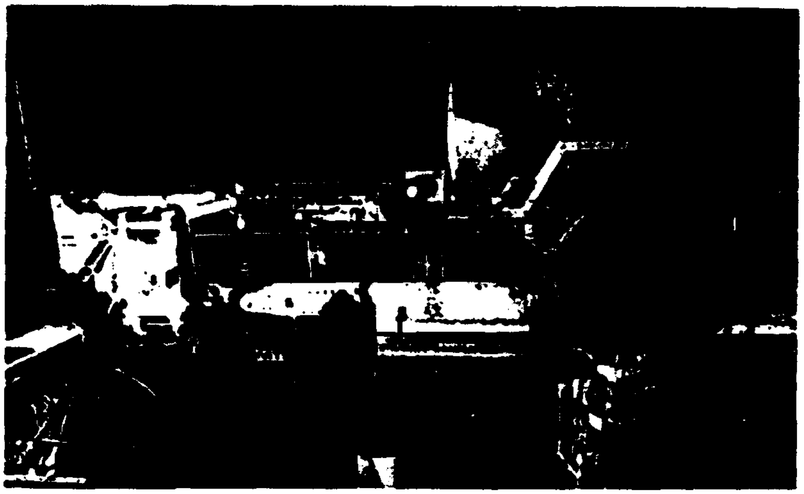

Figure 5-2. PMBS with M149A2 Trailer.

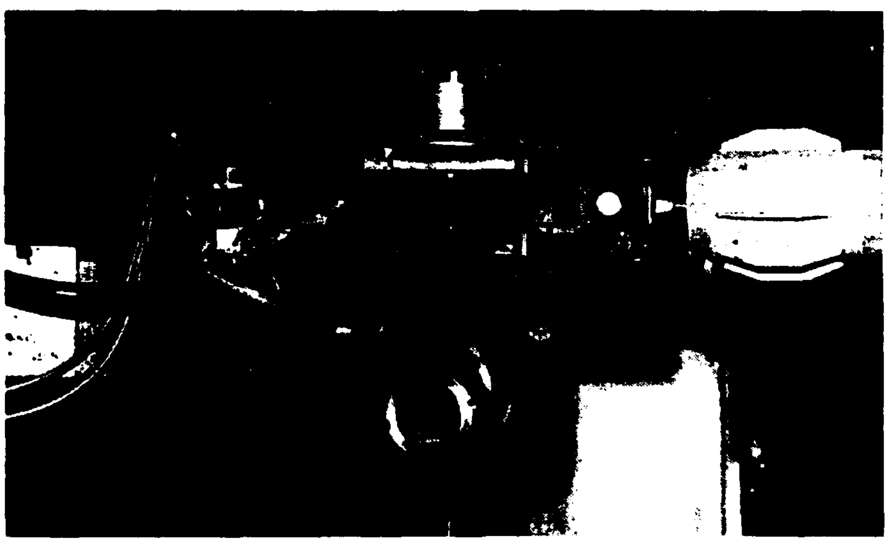

Figure 5-3. PMBS Lunette Clamping Hardware.

Table 5-1 PMBS Specifications and Achieved Values.

Parameter	Value (Goal)	Value (Achieved)
Trailer payload:	20,000 lbs	20,000 lbs
Displacement:		
Lateral	+- 4 inch	+- 5.25 inch
Longitudinal	+- 4 inch	+- 5 inch
Vertical	+- 7.5 inch	+- 8.62 inch
Pitch (passive)	+- 10 deg	+- 10 deg
Roll (passive)	+- 14 deg	+- 15 deg
Velocity:		
Lateral	+- 30 in/sec	+- 60 in/sec
Longitudinal	+- 30 in/sec	+- 51 in/sec
Vertical	+- 72 in/sec	+- 78 in/sec
Acceleration (moving mass):		
Lateral	5g (700 lbs)	16.7g (700 lbs)
Longitudinal	12g (1700 lbs)	16.1g (1700 lbs)
Vertical	17g (700 lbs)	26.4g (700 lbs)
Force:		
Lateral	3,500 lbs-f	11,700 lbs-f
Longitudinal	20,400 lbs-f	27,300 lbs-f
Vertical	11,900 lbs-f	18,480 lbs-f
Bandwidth: *		
Lateral	80 Hz	40 Hz
Longitudinal	80 Hz	40 Hz
Lunette vert	80 Hz	40 Hz
Spindle vert	40 Hz	40 Hz
Control Strategy:	Remote Parameter Control III	

* partly dependent on Trailer specimen.

5.2.3 458 MicroConsole™

The 458 MicroConsole™ is a configurable analog controller. It is a microprocessor-based control unit which houses the analog electronics for closed-loop control of a servo-hydraulic test system. Specifically the MicroConsole™ provides the following operating functions:

- Emergency stop
- On-Off, Hi-Low control of the hydraulic power supply and hydraulic service manifold
- Power storage allows soft shut-down in the event of electric power disruption
- Programmable, multi-function display
- Nine-digit event counter
- Display read-out in engineering units
- Separate interlocks for:
  - End of count

- Upper and lower limits
- Max absolute error
- Under peak detect
- Hydraulic pressure

- Individual and master span and set-points for all controlling channels
- Function generation (sine, triangle, and square waves)

The 458 MicroConsole™ can contain any combination of AC and/or DC controller cards and can be configured to operate with two- and three-stage servo valves. The controllers can be configured for any feedback transducer via circuit cards. The controller is a classic PID controller. The 458 performs closed-loop servo control functions given a command in the form of a voltage signal which can come from many sources, usually the 498 ASC™.

5.2.4 498 ASC™

The 498 Automated Site Controller™ (ASC) is the device which supplies up to 20 simultaneous channels of position/load commands to the 458. It also digitizes up to 40 simultaneous channels of simulator instrumentation data. The ASC™ is a fully functional, stand-alone test playback and monitor computer system. The test scenario is set up on the VAXstation™ 3100 and then downloaded to the 498 ASC™. Once the test is down-loaded to the 498, it can continuously supply the 458 with command signals, digitize data, and monitor the incoming data for trend and limit violations without need of the VAXstation™ 3100. The 498 also has digital filtering and down sampling implemented in hardware. The 498 ASC™ has 12-bit Digital-to-Analog (D/A) Conversion and 16-bit Analog-to-Digital (A/D) Conversion; both the D/A and A/D can sample at fixed incremental rates up to 2048 samples per second. The digital anti-aliasing filters have pass-band cutoff frequencies as great as 80 percent of the Nyquist rate for a given sampling rate. However, the largest frequency which can be measured is approximately 204 Hz.

5.2.5 VAXstation™ 3100 Computer

The VAXstation™ 3100 is a high-end workstation which the test engineer uses to do all of the test setup, editing, and analysis. The VAXstation™ runs the VMS™ operating system and uses the Motif™ Window System as a user interface. It also has Fortran and C compilers which are used to write in-house programs for data analysis and data file translation. Also resident on the 3100 is the RPC™ III software which allows the system to control a remote parameter such as acceleration or strain.

5.2.6 System Specifications

The system level specifications for the PMBS were carefully determined using a combination of computer-based dynamic models of some typical trailers and the proving ground data from the M832 Dolly Set. Careful analysis of the data produced from these tests described in the following sections led to the PMBS specifications previously presented in Table 5-1.

DADS computer-based models were created and simulated over various cross-country terrains in order to determine the design criteria of displacement, velocity, acceleration, and force. These high-resolution models were run on a Cray-2 Supercomputer which yields timely results from complex mathematical representations. Table 5-2 describes the DADS models which were run.

Table 5-2 DADS computer-based data collection scenario.

Vehicle Model	Weight(GVW)	Course	Speed
Hawk	9,407 lbs.	Churchville 6 *	30 mph
Hawk	9,407 lbs.	Letourneau 4 **	20 mph
M101A3	3,900 lbs.	Churchville 6 *	30 mph
M101A3	3,900 lbs.	Letourneau 4 **	20 mph
M200	6,178 lbs.	Churchville 6 *	30 mph
M200	6,178 lbs.	Letourneau 4 **	20 mph
M840	10,678 lbs.	Churchville 6 *	30 mph
M840	10,678 lbs.	Letourneau 4 **	20 mph

* From mild portion of Churchville B (0.25 in RMS).
** WES course used at half amplitude (0.60 in RMS).

This combination of simulations produced typical responses of many trailer classes over different courses and speeds. Displacement, velocity, acceleration, and force data at any point or axis of interest on the trailer are output from the model. The data were then analyzed for statistical content.

Proving ground gathered data were also used to determine the PMBS specifications. High-quality data were obtained from the M832 dolly set PQT at Aberdeen Proving Ground (APG). Forty-Two channels of instrumentation data were recorded by CSTA and transferred to TARDEC computers. These data further helped define the design criteria. Table 5-3 summarizes the proving ground testing scenario.

Table 5-3 APG data collection scenario.

Vehicle Model	Weight(GVW)	Course	Speed
M832	14,200 lbs.	Munson Gravel	24
"	"	Perryman	17
"	"	Churchville B	10
"	"	Belgian Block	15

5.3 M149A2 Tests

In addition to the four different tests conducted with the M149A2 Water Trailer, an analytical model was also made of the M149A2 trailer. (The analytical model is regarded as a test in this section.) Each test was performed for specific reasons. The tests are enumerated in Table 5-4 and are briefly described as follows:

- *Fixed Lunette Test* - Section 5.3.1
- *Proving Ground Test* - Section 5.3.2
- *DADS Simulation* - Section 5.3.3
- *PMBS Test Using Proving Ground Data* - Section 5.3.4
- *PMBS Test Using DADS Data* - Section 5.3.5

These tests were executed to (1) determine the performance of the PMBS when controlling remote parameters using proving ground data as input, (2) to determine the validity of using DADS model data as controller input, and (3) determine the improvements to our testing ability added by the PMBS.

Table 5-4 Summary of M149 Tests.

Test	Date	APG Courses
Fixed Lunette Simulator	Feb '93	Munson Gravel, Perryman 1, Perryman A, Churchville B (Rough & Mild),Churchville C, Belgian Block
Proving Ground Data Acquisition (1)	June '93	Munson Gravel, Perryman 1, Perryman Paved, Churchville B (Rough & Mild), Belgian Block
DADS Data Acquisition	Nov '93	Munson Gravel, Perryman 1, Churchville B (Rough & mild), Belgian Block
Pintle Motion Base Simulator (DADS Data as Input)	Nov '93	Same as DADS
Pintle Motion Base Simulator (Proving Ground Data as Input)	March '94	Same as proving ground

(1) CSTA Report Dated August 16, 1993 (TR No. STECS-AE-S-116)

5.3.1 Fixed Lunette Simulator

Prior to the acquisition of the PMBS, the PSL performed durability testing on lunette trailers by attaching their lunettes to a fixed pintle and then playing the profile of an APG course into the rear actuators at a given rate which corresponds to the trailer speed. Figure 5-4 shows a drawing of this test system. This method exercises the suspension system but does not adequately test the lunette area nor does it reproduce the forces input to the trailer through the lunette. The test provided the data necessary to accurately compare the PMBS method to the fixed-lunette method. There are two major inaccuracies involved in the fixed-lunette method of testing: (1) there is no motion imparted to the lunette, and (2) it was not possible to produce controlled trailer responses by playing the course profile into the tires via wheel platens. For further explanation of this test method see references 8, 9, and 10.

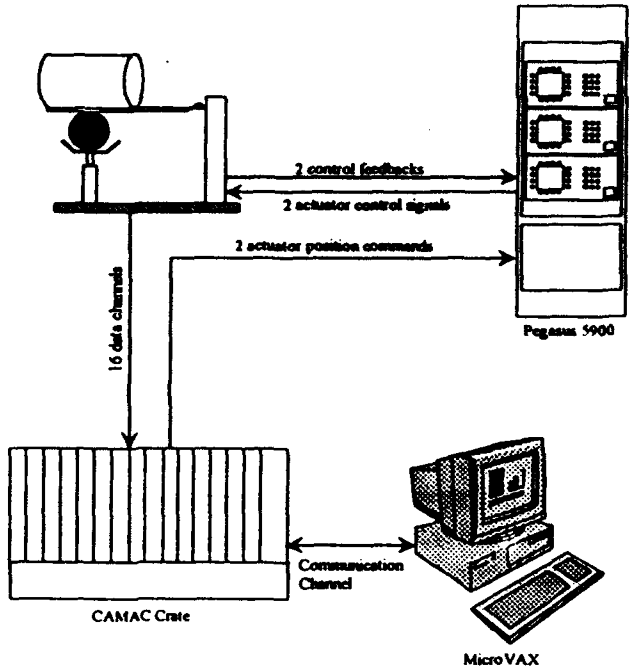

Figure 5-4. Fixed Lunette Test System.

This test was executed using a Computer Automated Measurement And Control (CAMAC) system. This is a modular system which can be configured in a number of different ways to meet the user's data acquisition and control needs. The configuration for this test used a timed D/A to convert digital data to analog voltage signals for a Pegasus 5900 controller. This D/A outputs two actuator commands at a rate of 100 samples-per-second. A data logger was used to sample the instrumentation signals from the trailer. Sixteen channels of response data were recorded for this test at a rate of 500 samples per second and were low-pass filtered at 100 Hz to prevent aliasing. The A/D has 12-bit resolution over a range of 20 Volts which yields a resolution of 4.88 mV per count. Table A-2 of Appendix A details the channels recorded for this test.

The data were recorded and then statistically analyzed and saved for comparison to the proving ground data and the PMBS test data. The data are statistically summarized in Appendix A in Tables A-3 through A-19.

This test was executed prior to the proving ground test and was run on courses matching those that were run at the proving ground. Table 5-5 shows the courses/speeds chosen. All of these courses are taken from the May 1992 APG course profile library maintained at the PSL.

As stated in Section 1.2, this method tends to overtest the trailer suspension. Because of this, some of the courses were not played at full amplitude as it was feared the trailer would bounce off of the simulator. The Churchville B profile was not run at full amplitude due to the limited stroke of the actuators. The stroke is ± 6 inches while Churchville B demands excursions as great as 15 inches. Consequently the simulations were run at 40 and 60 percent of the full amplitude. The Belgian Block profile was not run at 100 percent amplitude to protect the trailer and simulator. As with Churchville B, the simulations were reduced to 40, 50, 60, and 75 percent, depending on the speed and severity. Although these attenuated runs are not directly comparable, they are useful for the comparison of test methods in general because profiles are routinely attenuated in fixed-lunette testing. Table A-1 of Appendix A lists all of the data runs.

The fixed-lunette test produced spindle accelerations which were equal to or greater than the proving ground accelerations in most cases. This is even the case when the profile was not used at full amplitude. The longitudinal lunette acceleration, on the other hand, generally has the same energy level as that associated with the proving ground, but the longitudinal lunette strain is significantly less than the strain measured at the proving ground. This is due to the nature of the fixed-lunette simulator's lack of dynamic input to the lunette. Statistical summaries of the data are presented in Appendix A and comparisons to the proving ground data are presented in Appendix H.

Table 5-5 Description of Fixed-Lunette Test Scenarios

APG Course	Course RMS (100%)	Portion	Speeds Run
Belgian Block	0.70 in	Whole course	16, 19, 21 mph
Churchville B (Rough)	3.15 in	13,000 - 15,000 ft.	10, 13, 16 mph
Churchville B (Mild)	0.69 in	6,000 - 8,000 ft.	20, 23, 26 mph
Churchville C	0.35 in	0 - 2,000 ft.	18, 21, 24 mph
Munson Gravel	0.30 in	0 - 2,000 ft.	20, 23, 26 mph
Perryman 1	0.41 in	0 - 2,000 ft.	14, 17, 20 mph
Perryman A	0.35 in	0 - 2,000 ft.	18, 21, 24 mph

5.3.2 Proving Ground Test

The proving ground data collection exercise provided the proper acceleration and strain information required for RPC™ III control. It also provided correlation channels which helped determine the accuracy of each method of lab testing. This test was run to record response data which precisely quantify typical service-life dynamics. It was run at varying speeds on six different APG course profiles which are described in Table 5-6. Thirty-seven data recording runs were made during the test which are shown in Appendix B Table B-1.

Twenty-three channels were recorded. The data were sampled at a rate of 1000 Hz and low-pass filtered at 100 Hz to prevent aliasing. They were sampled with 10-bit resolution using a telemetry system. The test was executed in June 1993. See Reference (7) for a complete description of the proving ground test. The statistics for the run are summarized in Tables B-3 through B-15.

The data recorded were separated into two groups for simulator usage: (1) RPC™ channels and (2) correlation channels. RPC™ channels are those that can be used as input to the RPC™ process. These include spindle and lunette acceleration and lunette strain in the vertical and longitudinal directions. The correlation channels are those which cannot be used as input to the RPC™ process but serve as a means of comparing all other tests to the proving ground test. These include all other accelerometers, rate transducers, and linear potentiometers. It is desirable to carefully choose the correlation transducers and locations so that they provide an accurate means of comparing the damaging effects of all test methods. Table B-2 describes the data channels recorded in the proving ground test.

Table 5-6 Data Recording Courses and Speeds for M149A2 Proving Ground Test at APG.

APG Course	Length (approx.)	Speeds
Belgian Block	1,850 ft	10, 15, 18 mph
Churchville B (Rough)	2,200 ft	5, 10, 13, 16 mph
Churchville B (Mild)	1,260 ft	15, 20 mph
Munson Gravel	1,860 ft	20, 26 mph
Perryman 1	1920 ft	15, 20 mph
Perryman Paved	1,700 ft	25, 35, 43 mph

5.3.3 DADS Test

The DADS computer-based method is a highly detailed, general-purpose modeling and simulation method for determining the spatial, transient-dynamic response of controlled, articulated multibody mechanical systems to excitation by irregular external and internal forces and disturbances. The method consists of a library of subroutines defining primitive rigid-body, kinematic-joint, control-element, and force building blocks that can be combined in numerous ways to assemble complex system models to the level of detail and accuracy deemed necessary for a given problem. The DADS program consists of three main parts, a preprocessor, main processor, and postprocessor. The preprocessor allows much of the system's parametric and topological properties to be defined in an interactive environment without being concerned with the supporting mathematics. The preprocessor then sends this information to the main processor, which uses it to assemble the equations of kinematics and dynamics. The main processor also has several user interface subroutines which allow more detail to be added to the model than possible with primitive building blocks. This feature makes the representation of highly nonlinear vehicle system properties possible and yields more accurate models. The main processor also automatically integrates the resulting equations of motion for a specified period of time and outputs state variables at regular specified time intervals. The postprocessor allows these state variables to be output to an external file.

Several points of interest (POI) were defined in the model of the M149A2 water trailer. All of these POIs correspond to instrumentation locations in the original proving ground test. The data recorded at the POIs relate to either RPC™ transducer or correlation transducer output. The RPC™ POIs output data of wheel spindle and lunette accelerations and forces. The data output from the other POIs are for correlation and correspond to the proving ground channels of frame acceleration, angular rate, and suspension travel. There were 13 DADS computer simulations made on the five courses shown in Table 5-7 with at least two speeds for every course. There were 22 channels recorded from these simulations at a rate of 100 samples per second.

Table 5-7. Courses and speeds from DADS computer-based runs.

APG Course	Length (approx.)	Speeds
Belgian Block	500 ft	11, 15, 18 mph
Churchville B (Rough)	500 ft	5, 10, 12, 14 mph
Churchville B (Mild)	500 ft	13, 19 mph
Munson Gravel	500 ft	20, 25 mph
Perryman 1	500 ft	15, 20 mph

5.3.4 PMBS Test With Proving Ground Data as Input

In this test the trailer is placed on the PMBS and the 5 RPC™ channels, recorded at the proving ground, are used as inputs to the RPC™ process. The RPC™ process uses these data to derive drive commands which are used to physically "shake" the trailer. For a detailed discussion of this process see Section 5.4. Because this test is the most important one, the engineers and technicians of the PSL and MTS Systems Corporation spent many ours optimizing the RPC™ process.

Since the proving ground data were used to develop the drive commands, the course and speed selections are limited to those for which there are proving ground data. One run from each bump course was used to develop a drive for each course. It would not be beneficial to develop a drive command for each of the 37 proving ground runs, so it was decided to run the fastest speed from every course since this represents the "worst case." It was assumed that if the highest speed could be reproduced then the lower speeds could also be reproduced because lower speeds behave more linearly. Therefore, Table 5-8 indicates the course/speed scenarios which were used to develop drive commands. Also included in this table is the number of iterations required for convergence. (For an explanation of convergence see Section 5.4.4.)

In addition to the 5 RPC™ transducers, there were also 11 correlation channels recorded for a total of 16 channels. There were only 16 channels of data recorded because, at the time of the test setup, there were only 16 data acquisition channels available. These 16 channels correspond to the most important data channels from the proving ground from the standpoint of correlation of results. Most of the channels not recorded were those which were orthogonal to the primary axis of interest.

The data were sampled at a rate of 204.8 Hz and anti-alias-filtered at 81.92 Hz with a digital filter. The sampling circuitry uses 16-bit resolution; this amounts to a resolution of 0.305 mV with a full-scale value of ±10 V.

Table D-1 details the data channels that were recorded. Statistical summaries of the recorded data are presented in Tables D-2 through D-8. The Data Analysis section (5.5) of this report presents the results and accuracy of the simulation technique, where this topic will be covered in greater detail.

Table 5-8 Iterations required for typical bump courses.

APG Course	Speed (mph)	Proving Ground Run #	Iterations Required
Belgian Block	18	010	17
Munson Gravel	26	003	10
Perryman 1	20	037	9
Perryman Paved	43	016	13
Churchville B (Mild)	20	025	13
Churchville B (Rough)	10	028	14
Churchville B (Rough)	16	032	16

5.3.5 PMBS Test With DADS Data as Input

This test is very similar to the test described above, except that DADS data are used as inputs to the RPC™ process. The results of this test depend directly upon the accuracy of the DADS model, since this process controls the five input channels which are generated by a DADS model.

This test was run on five different profiles at speeds which correspond to the original DADS runs (Section 5.3.3). One run from each bump course was executed using the highest speed for each, unless the scenario was unsafe as determined by the test engineers and technicians. The course/speed scenarios for this exercise are shown in Table 5-9.

The data acquisition, setup, and specifications are identical to those described in the previous section (5.3.4). The data recorded are statistically summarized in Appendix E, Tables E-1 through E-11. The results are compared to the proving ground data in Appendix H.

The spindle accelerations are generally equal to or greater than those measured at the proving ground. This is directly caused by the DADS model, since the simulator's reproduction of vertical spindle accelerations is accurate out to 60 Hz. The lunette accelerations are generally less than the proving ground lunette accelerations. This is probably due to the lack of slop or lash at the pintle/lunette interface as represented in the model. Also, the lunette axial strain is greater in the lab than at the proving ground. This is caused by phenomena described in Section 5.4. A comparison between the results of this test and the proving ground data is shown in Section 5.5 and Appendix H.

Table 5-9 Courses and speeds from DADS data runs.

APG Course	Length (approx.)	Speed	Iterations
Belgian Block	500 ft	11 mph	20
Belgian Block	500 ft	15 mph	10
Churchville B (Mild)	500 ft	13 mph	22
Churchville B (Mild)	500 ft	19 mph	18
Churchville B (Rough)	500 ft	10 mph	19
Churchville B (Rough)	500 ft	12 mph	17
Churchville B (Rough)	500 ft	14 mph	20
Munson Gravel	500 ft	20 mph	25
Munson Gravel	500 ft	25 mph	19
Perryman 1	500 ft	15 mph	19
Perryman 1	500 ft	20 mph	18

5.4 Test Method Development

The test method using the PMBS was developed and optimized. The engineers and technicians of the PSL worked many hours trying to extend the performance of the simulator to the highest limits possible. The performance goal was to control input data from 0.6 to 60 Hz. To accomplish this goal, several hurdles had to be overcome. This section details the process taken, control problems encountered, solutions, and recommended control schemes. The final control schemes are shown in Table 5-10.

Table 5-10 Description of Control Modes.

Axis of Control	RPC™ Parameter	Bandwidth
Lunette Lateral	Acceleration	0.6 - 40 Hz
Lunette Vertical	Acceleration	0.6 - 40 Hz
Lunette Longitudinal	Strain	0.6 - 40 Hz
Left Spindle Vertical	Acceleration	0.6 - 60 Hz
Right Spindle Vertical	Acceleration	0.6 - 60 Hz

5.4.1 Longitudinal Lunette Acceleration Control

Originally, the three orthogonal accelerations were used to control the motion of the lunette. This worked well for all of the runs in all three directions out to 37 Hz. Using this method, the three lunette accelerations matched the proving ground accelerations very accurately.

It was assumed that if the acceleration at the lunette matched the proving ground acceleration, the correlation channels would also match to a high degree of accuracy. However, the longitudinal lunette strain from the simulator did not correlate to the proving ground measured strain. Figure 5-5 shows the frequency domain comparison of proving ground vs. simulator strains for the Belgian Block course at 18 mph. This discrepancy in strains is caused by the lunette coupling mechanism of the simulator. The simulator lunette coupling adds mass to the trailer at the lunette which causes high force to accompany normal longitudinal acceleration when reproducing an impact event at the lunette. Longitudinal acceleration will cause an inertial reaction against this added mass. In other words, the simulator produces extra force (i.e. strain) to accelerate this added mass. Since strain is directly related to damage while acceleration is not, it was decided that it is more important to reproduce the correct strain levels than the correct accelerations at the lunette.

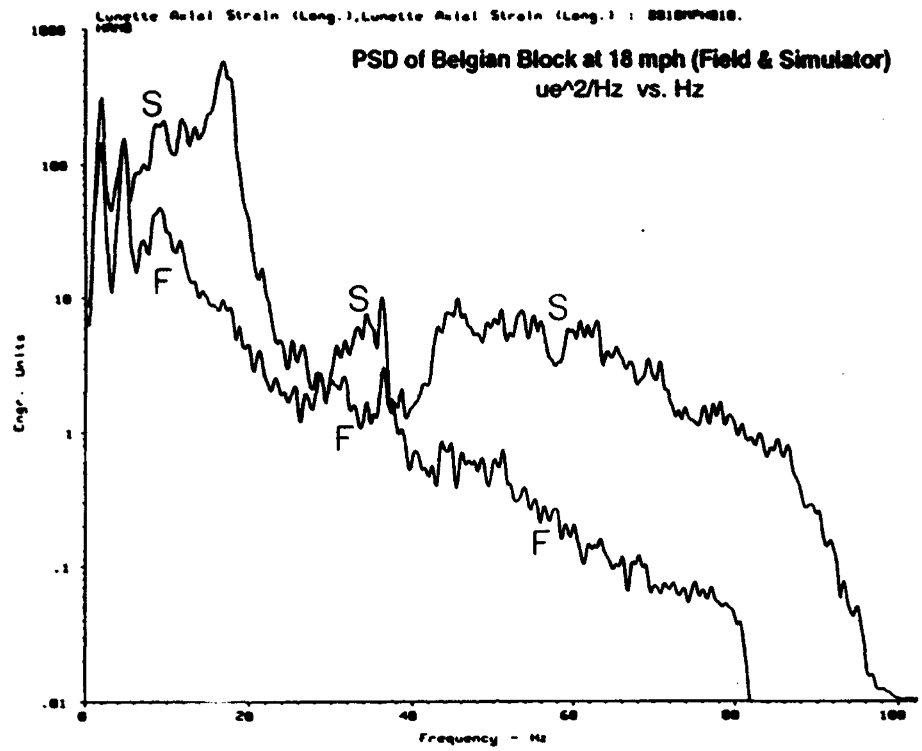

Figure 5-5. Longitudinal Strain Using Acceleration as a Control Parameter

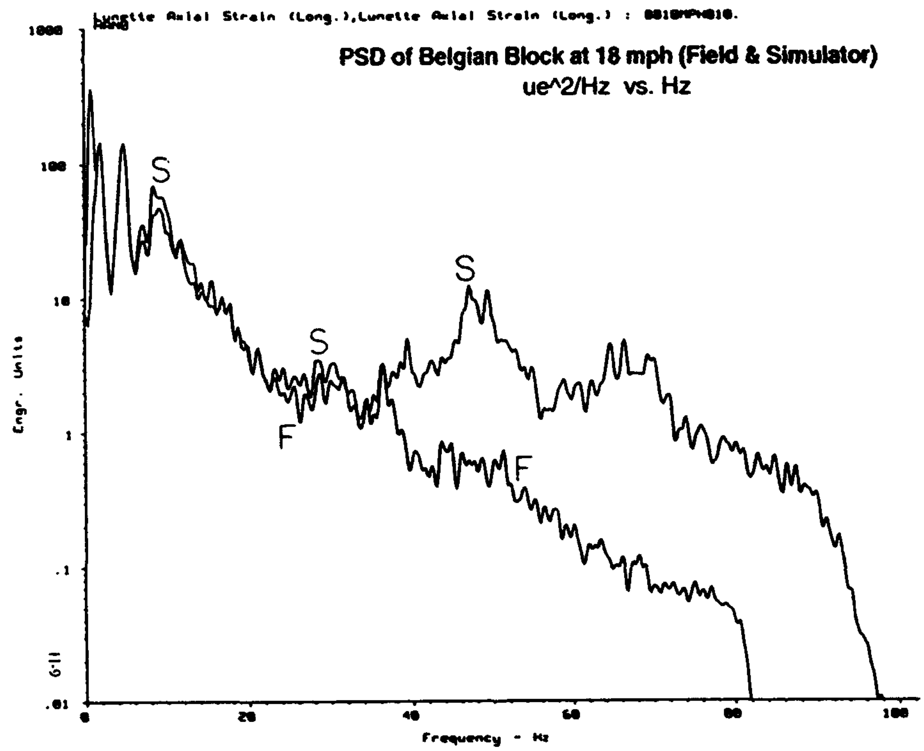

Figure 5-6. Longitudinal Strain Using Strain as a Control Parameter.

5.4.2 Longitudinal Lunette Strain Control
Although strain serves as a better longitudinal control parameter than acceleration, it also has limitations as a control parameter. Some of these are related to gage location, gage resolution, and resonance modes of the trailer and lunette. Due to these limitations, the bandwidth of control is only slightly increased from 37 Hz. to 40 Hz. This is because there are several control problems which manifest themselves in frequencies past 40 Hz. For a detailed description of these problems see section 5.4.4. Although the bandwidth has not increased appreciably, the strain levels within the region of control (0.6 - 40.0 Hz) match the strains measured at the proving ground as shown in Figure 5-6. Since strain is the control parameter, the engineer knows that comparable damage is being inflicted on the trailer in the lunette area. When controlling acceleration this is not always the case as stated in Section 5.4.1. Based on these observations, strain was used as the RPC™ parameter for the lunette longitudinal channel. The bandwidth of this channel remained the same at 0.6 to 40 Hz.

5.4.3 Vertical Spindle Acceleration Control
The trailer wheel spindles were acceleration-controlled in the vertical direction. (Vertical is the only currently available channel of control for the wheel spindles at the PSL.) Acceleration was used because the wheel is an inertially reacted body for the most part. It is the parameter of choice in the automotive industry for vertical spindle inputs. The spindle accelerations were controllable out to 60 Hz because the axle is decoupled from the frame of the trailer by the springs and shock absorbers. There was a tendency to overshoot slightly at the suspension's natural frequency (approximately 10 Hz) but successive iterations eliminated this overshoot. For a discussion of iterations see section 5.4.4.

5.4.4 RPC™ Process
The simulator uses the RPC™ III software to replicate the same spindle/lunette accelerations/forces in the lab which were experienced at the proving ground. The RPC™ process described in Appendix I was used to reproduce the proving ground dynamics of the M149A2 trailer in the lab. A block diagram of this process is shown in Figure 5-7. This process is straight forward, logical, and consists of the following steps.

Step 1 - Measurement of proving ground response data.
In this case, CSTA recorded RPC™ and correlation transducer channels according to our specifications. The recording of RPC™ channels is a necessary part of every test. They can be recorded at the proving ground or in a computer-based model as shown earlier. RPC™ transducers are oriented in such a way as to be primarily influenced by only one input channel in the desired frequency range on the simulator. This is an ideal case; sometimes it cannot be determined if the locations are suitable until a Frequency Response Function (FRF) of the system is measured. Correlation transducers record extra channels which help the engineer know if the simulator is reproducing proving ground events correctly. The Belgian Block course at 18 mph produces intense random vibration and therefore represents an adequate case to analyze, so throughout the rest of this report it will be used as an example. Figure 5-8 shows the time-history plots of the 5 RPC™ data channels recorded at the proving ground from the Belgian Block course at 18 mph.

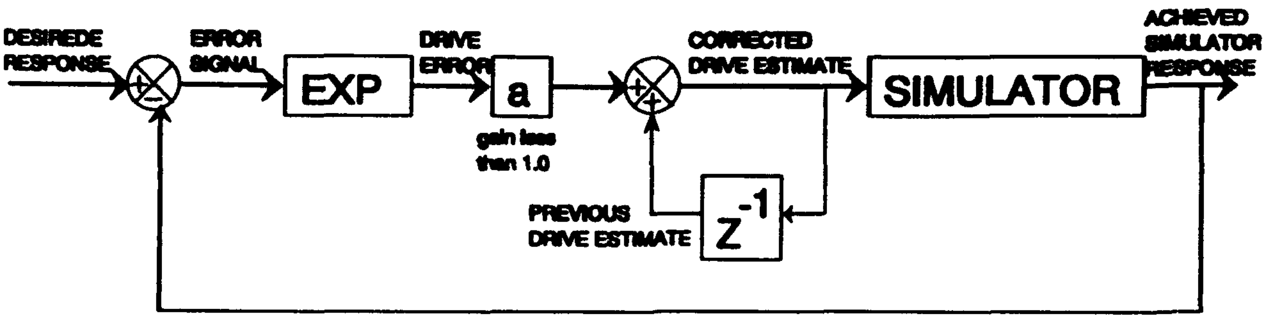

Figure 5-7 Block Diagram of RPC™ process

Step 2 - System Characterization.
Next the trailer was mounted on the simulator and characterized by measuring the system FRF. This system includes all characteristics between the drive command and the recorded response, such as the trailer, mechanical, hydraulic, and electrical characteristics of the simulator and control system, and the smoothing and anti-aliasing filters of the 498 ASC™. Figure 5-9 is a plot of the FRF used for the majority of the simulations.

The FRF was measured by playing shaped noise into each of the input actuators of the simulator one channel at a time. This noise is shaped in the frequency domain by setting the energy content of the noise at a particular frequency to be equal to $A*(1/f^N)$. Familiar terms for noise shaped in this fashion are white noise (N=0), pink noise (N=1), and brown noise (N=2). The values of N used in this test generally ranged from 1.4 to 3.0 depending on the channel and the frequency range.

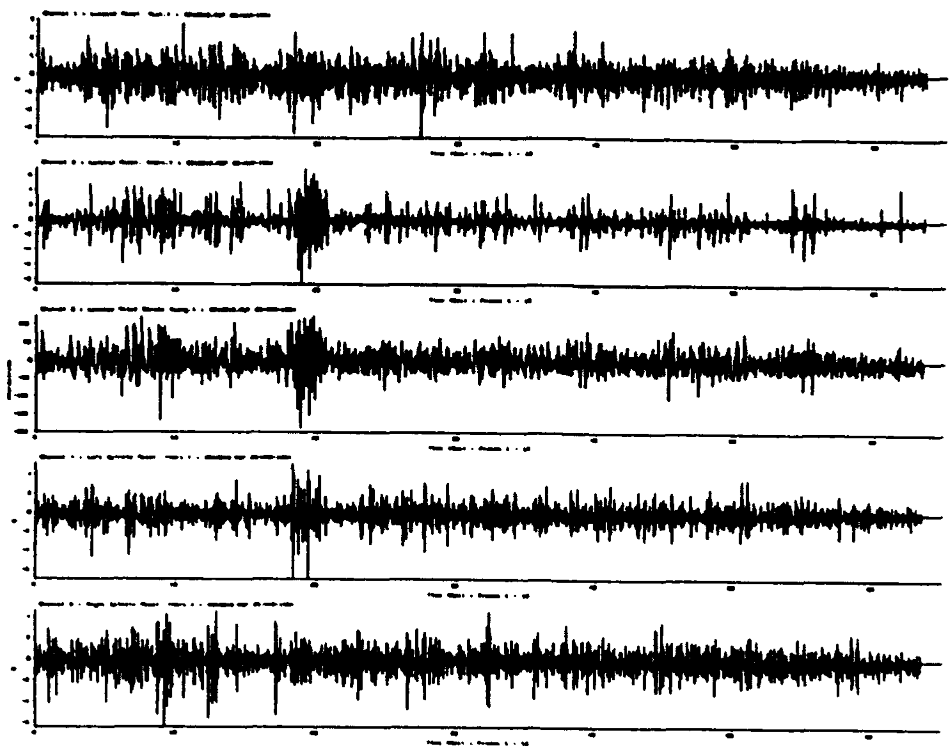

Figure 5-8. Time Histories of RPC™ channels (Belgian Block at 18 mph).

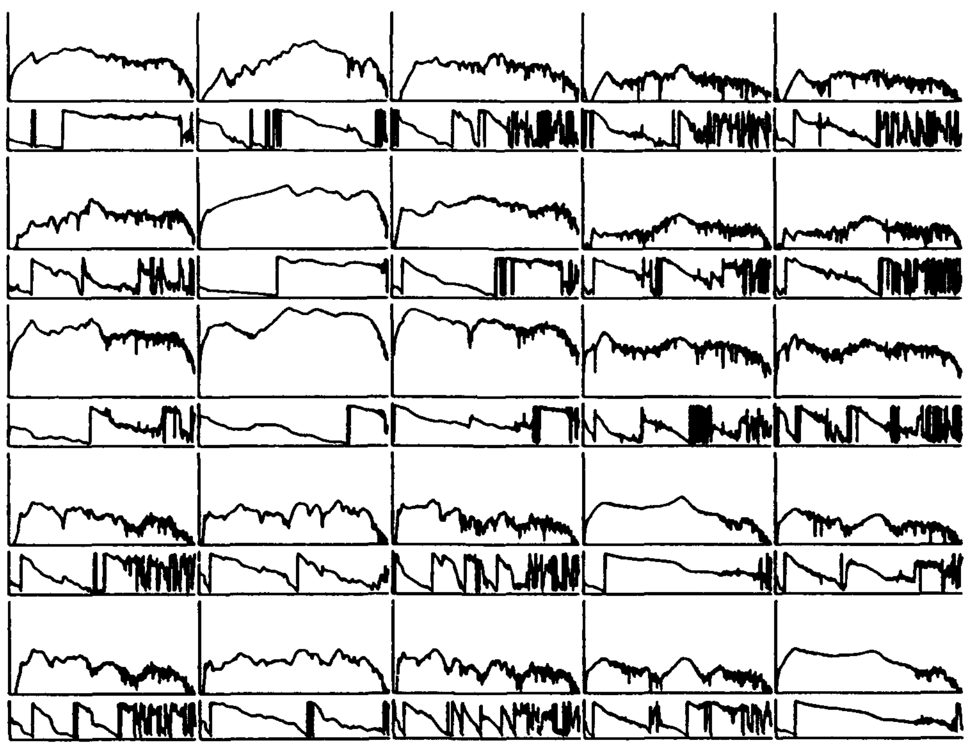

Figure 5-9. FRF of the PMBS/M149A2 System

Some of the channels require different shapes in different frequency ranges, such as the spindles, for which N=2 from 0 to 40 Hz and N=3 from 40 Hz to the Nyquist rate. Both the shape and magnitude of the noise signal are very important because the PMBS/trailer system is nonlinear. This can be most clearly seen in the wheel spindle response. Figure 5-10 plots two FRFs of different shapes resulting from the nonlinearity of the system. Dramatic differences are noted, especially in the 10-Hz region. The nonlinear system requires the use of one FRF for severe courses such as Belgian Block and another FRF for mild courses such as Munson Gravel. It is clear that the shape and characteristics of the FRF are highly dependent upon the magnitude and shape of the input noise. In summary, the shaped noise which influences the system FRF must be carefully generated by considering the proving ground data and trying to match the energy levels of the noise response to the proving ground data.

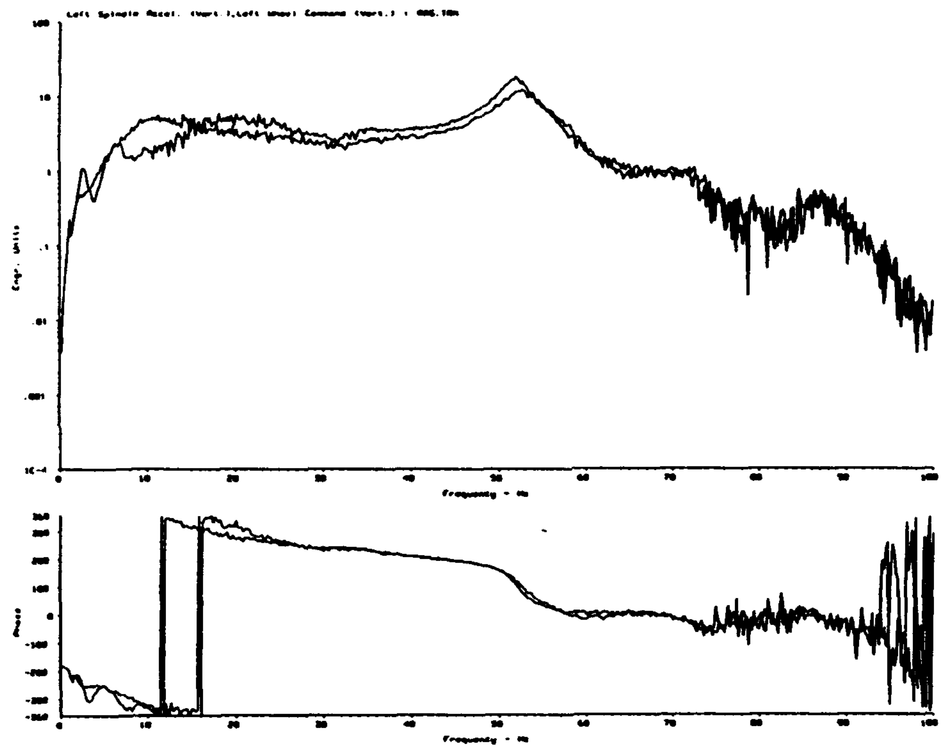

Figure 5-10. Demonstration of nonlinearities of Spindle Accelerations

Step 3 - Choose Simulator Bandwidth.

Once an FRF is measured, partial coherences are calculated to help determine which frequency regions are easily controllable--and those which may be difficult. The plot of the partial coherence can be seen in Figure 5-11. Coherence reports the percentage of the output which is linearly related to the input of each channel. Partial coherence can measure cross-channel contributions. A channel is generally controllable if it has partial coherence above 0.7 on the diagonal. It is desired that the on-diagonal partial coherence terms be close to 1.0 throughout the control bandwidth.

The bandwidth of the simulator is determined by two factors: (1) the bandwidth of the data which are to be reproduced, and (2) the controllability of the simulator throughout this bandwidth. Ideally, the simulator should be controllable throughout the region which is to be reproduced. However, the plots of the partial coherences indicate several problems in the frequency ranges from 40 to 60 Hz. The goal was to control up to 60 Hz. The control bandwidth, however, is limited to 40 Hz by the following:

1) *Vertical acceleration resonance.* The vertical acceleration FRF (Figure 5-9, Element 2,2) shows a gentle resonance at 43 Hz. Although this is not a very sharp resonance, it consistently caused the achieved response to overshoot the desired response. This overshoot could not be eliminated by tuning the servo-control system or changing iteration gains. The resonance is most probably a structural resonance and is characteristic of the trailer/simulator system. This resonance also prevents good control in the region around it and therefore this region is eliminated from the control bandwidth of the simulator.
2) *Longitudinal strain notch.* Secondly, the longitudinal strain FRF (Figure 5-9, Element 3,3) has a sharp notch at 41 Hz. This notch also causes control problems in the immediate region surrounding it. When the FRF is inverted (a necessary part of every RPC™ process), the inverse FRF has a sharp resonance at this frequency. This resonance in the inverse overcompensates for the notch in the FRF and causes large amounts of overshoot at 41 Hz. Also, upon inversion the notch leaks into the other control channels as a resonance and causes overshoot in them as well.
3) *Cross-coupling.* Thirdly, the partial coherence (Figure 5-11) indicates that the vertical actuator strongly influences both the vertical and longitudinal responses in the ranges above 40 Hz, thus mathematically over-constraining the system. Also, Figure 5-11 shows that the longitudinal input does not have control of any channel past 40 Hz. The system is trying here to control to two inputs with essentially only one degree of freedom. The simulator matches the vertical acceleration but overshoots the longitudinal strain by as much as a decade in the frequency regions above 40 Hz. This control problem is probably caused by transducer location and trailer/simulator characteristics.

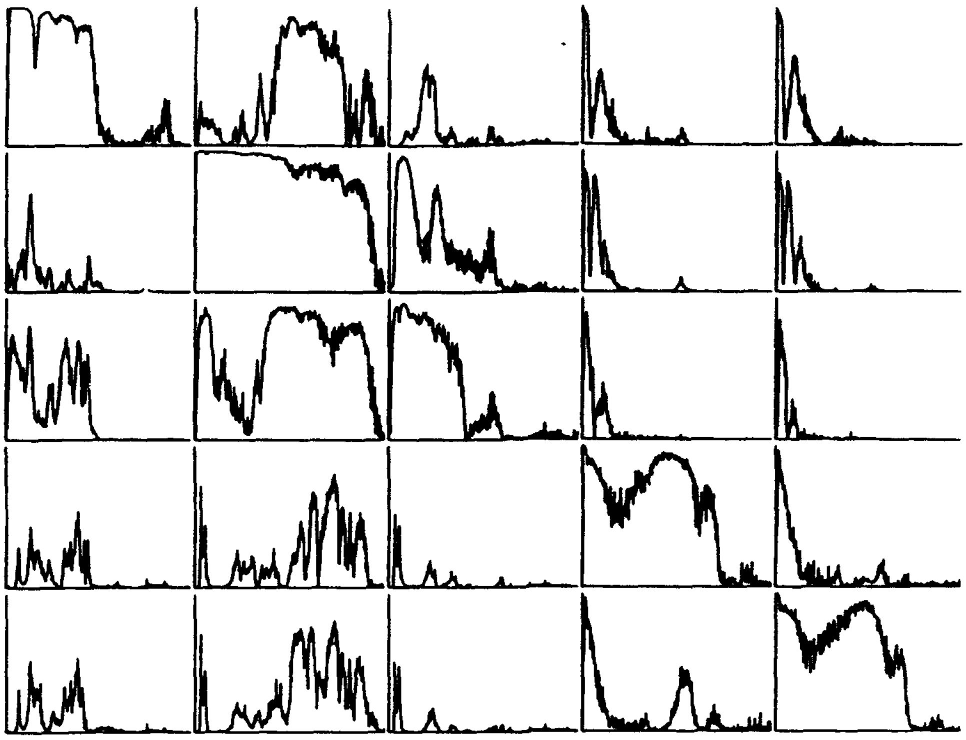

Figure 5-11. Partial Coherences of PMBS/M149A2 System

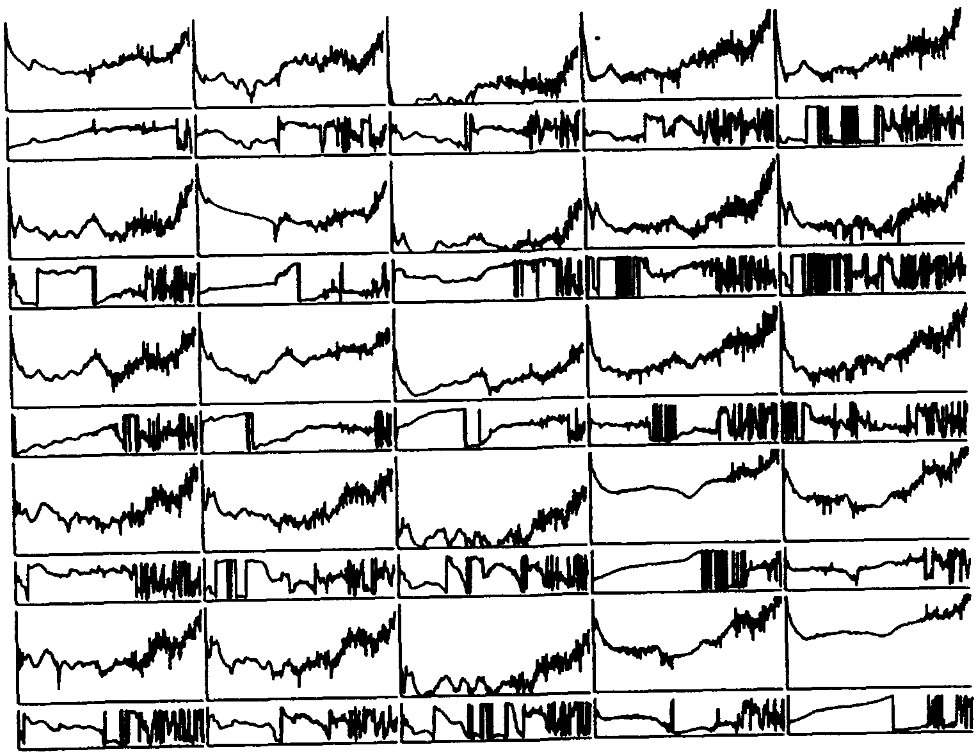

Figure 5-12. Inverted FRF of PMBS/M149A2 System.

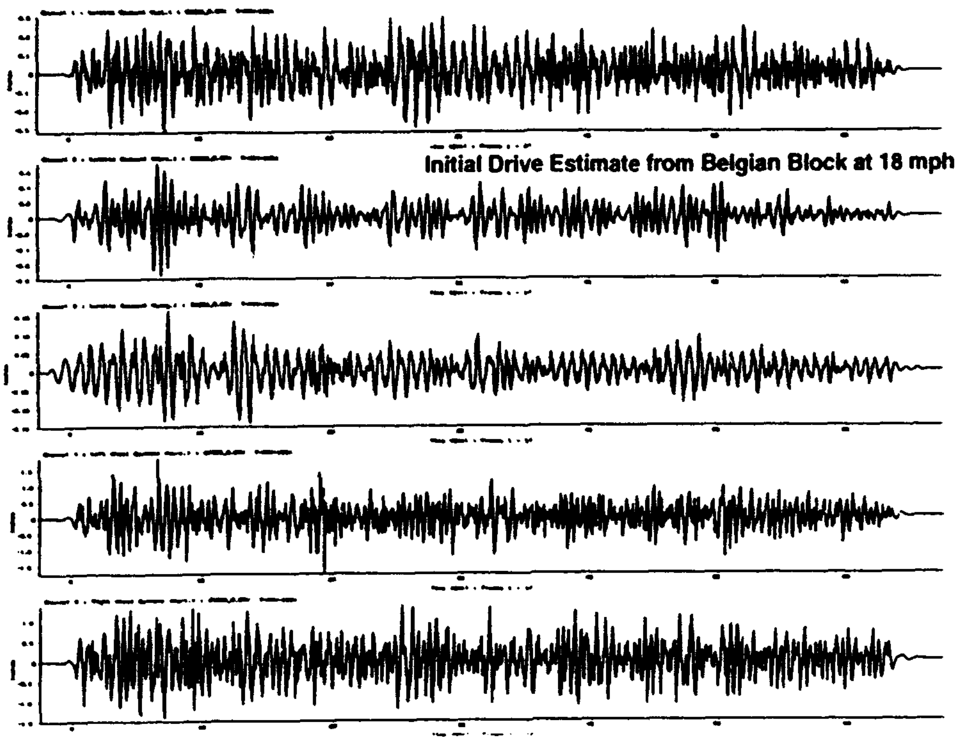

Figure 5-13. Initial Drive Estimate of PMBS/M149A2 System (Belgian Block at 18 mph).

These three control limitations forced a reduction in the simulator bandwidth from 60 Hz to 40 Hz. The above mentioned limitation of 40 Hz, although well short of the goal of 60 Hz, is a considerable improvement over the traditional closed-loop servo-hydraulic control used in the past.

Step 4 - Calculate Drive Estimate.
Once the PMBS bandwidth was set at 40 Hz, the proving ground data were filtered to 40 Hz using a box filter. The FRF was inverted and band-limited using the same cutoff. The inverted FRF can be seen in Figure 5-12. The inverted, band-limited FRF is called an Expanded Matrix. The Expanded Matrix is then used to determine an initial drive command estimate. The initial drive estimate is shown in Figure 5-13. The PMBS drive estimates are largely dependent on the proving ground data sets. Selected proving ground sets input to the process include the most severe runs from each terrain as given in Table 5-8.

Step 5 - Iterate.
Iterations can begin once the initial drive estimate is calculated. In Figure 5-7, the iterations are represented by the "closing of the loop" with negative feedback and also the positive feedback of the previous drive estimate. The iteration process consists of playing the original drive estimate into the simulator and recording the RPC™ transducers. There should be one RPC™ transducer

for every input channel; in this case there are five input channels. When the response is recorded, it is filtered with the same filter used to generate the desired response. Nominally, the filtered response will be less in magnitude than the desired response. The filtered response is subtracted from the desired response yielding an error signal. This error is then converted to a drive error by convolving it with the time domain representation of the expanded matrix. The drive error is then multiplied by a gain of less than one to account for nonlinearities. This attenuated drive error signal is then added to the original or previous drive estimate to yield another drive estimate, which represents the completion of one iteration. The drive estimate is played into the simulator and the cycle is continued until the ratio of RMS error over the RMS of the desired data stops decreasing or crosses a given level of acceptable error.

This ratio is usually a good indication of how the iterations are progressing but can be deceiving at times. The classic case is when there are a lot of sharp spikes in the desired response data. RPC™ will match the peaks fairly well but there will be a slight phase shift between desired and achieved responses, causing a large error. This type of error can be misleading because it is caused by minor phase differences not amplitude differences. Phase error can be dismissed as inconsequential. This phase error phenomenon is demonstrated in Figure 5-14.

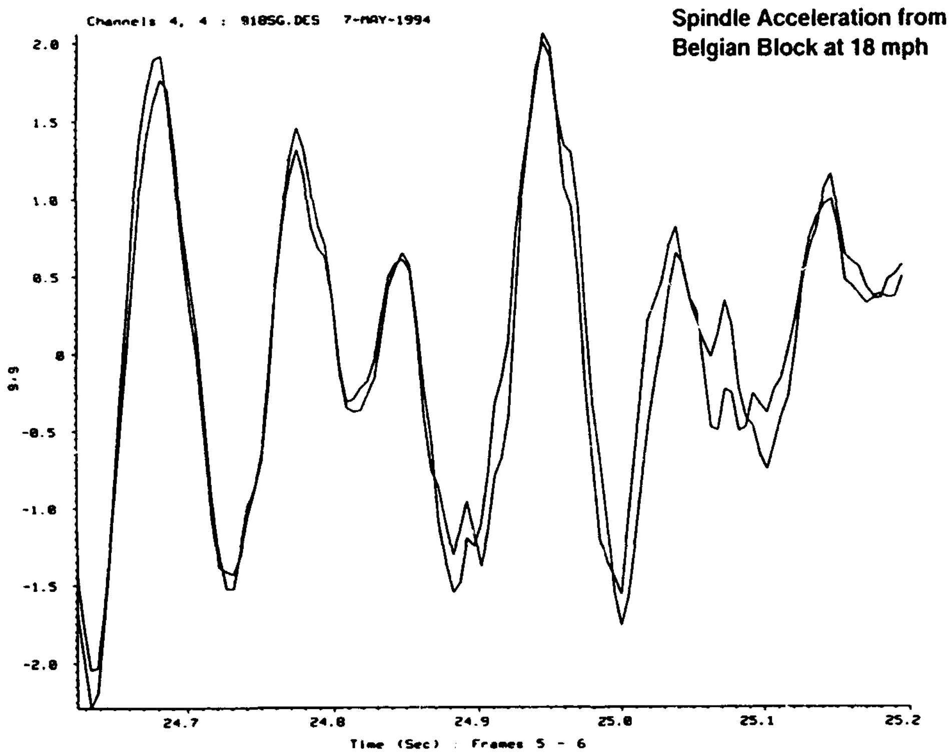

Figure 5-14. Demonstration of Phase Error (Belgian Block at 18 mph).

Seventeen iterations were run on Belgian Block. During iterations, the desired response must be slowly approached by the achieved response over several iterations, because of nonlinearities.

5.5 Data Analysis

5.5.1 General

Data were recorded, analyzed, and results are given for all testing. Several of the tests described in previous sections are compared to each other in this section. These comparisons consist entirely of comparing transducer outputs from one test with those of another, on a channel by channel basis.

As previously stated, the APG data were filtered at 82.0 Hz (80 percent of the Nyquist rate) when they were down-sampled from 1000 points per second to 204.8 points per second. The data from the PMBS test were sampled at 204.8 Hz and digitally filtered at 81.92 Hz. Both data from the proving ground and simulator have had the average value removed but are otherwise unaltered. The average value was not important for comparison purposes and represented arbitrary offsets inherent in a given transducer. The data from the proving ground are naturally correlated with the data from the simulator because the drive commands were generated from the proving ground data. This allows the comparison of any two signals from these tests in both the time domain and the frequency domain. Since the PMBS test was only controlled to 40 Hz, any response data correlation between the frequencies of 40 Hz and 82 Hz is strictly coincidental.

5.5.2 Comparisons in the time domain

Meaningful comparisons in the time domain necessitate that the signals to be compared are correlated in time. This section will compare the recorded simulator data when using proving ground data as input to the actual proving ground data, since these are the only tests which are naturally correlated in time. These comparisons consist of two separate entities, (1) time domain plots of desired and achieved data, and (2) error analysis in the time domain, including the following statistics:

- Maximum Absolute Error,
- Average Absolute Error,
- Maximum Relative Error,
- Average Relative Error,
- Cumulative Relative Error Histogram,

5.5.2.1 *Plot Comparisons.* The time plots are from the following courses and speeds: Belgian Block at 18 mph, Churchville B at 16 mph, Perryman 1 at 20 mph, and Munson Gravel at 26 mph. Appendix F contains these plots. Only the critical signals from these four runs are included in this appendix due to the overwhelming volume of the information. In Appendix F, for the Belgian Block course, each data channel is first shown from beginning to end to document how the run converged as a whole and then shown over the range of 18 to 20 seconds so that the signals can be compared in detail. This particular two-second section was chosen because, at this point all of the pertinent channels are experiencing a major transient event and the signal levels are relatively high. When comparing the time histories in other areas (where the signal maximum is considerably smaller), the time histories do not match as well (nor is it as important that they match). RPC™ III seems to control the more robust events in a time history better if it contains both severe and mild data. The data compared here have had the mean removed and have a bandwidth of 81.96 Hz, although the test was controlled to 40.0 Hz for the lunette channels and 60 Hz for the spindle channels.

The vertical lunette accelerometer from the Belgian Block run can serve as an example of such a comparison. Figure 5-15 shows the proving ground data compared to the simulator data for the entire length of the run. Also, Figure 5-16 shows the section from 18 to 20 seconds so that the quality of reproduction can be seen in detail. As demonstrated in the figures, the simulator matches the peak accelerations fairly well and this matching is typical of its ability to reproduce proving ground dynamics.

Some channels will not match as well as they should because there were differences in the position and/or type of transducer used at the proving ground as opposed to the lab. The suspension travel channels fall into this category. At the proving ground, the suspension travel was measured directly along the shock absorber while in the lab it was measured by a string potentiometer going from the spindle up to the body of the trailer. The proving ground transducers were mounted closer to the center of the trailer than the lab transducers. This has three different effects on the recorded data:

1) The proving ground transducer is less sensitive to its respective spindle's displacement while the lab transducer is more sensitive, because of its position.
2) The proving ground transducer is more susceptible to cross coupling from the opposite spindle displacement because it is positioned closer to the center of the axle.
3) Also the lab transducer is sensitive to lateral and longitudinal motions of the axle due to its position.

The spindle displacement data would have matched better if the same transducers and locations had been used both at the proving ground and in the lab. This was not possible, however, so these differences in transducer location and type should be considered when comparing these channels.

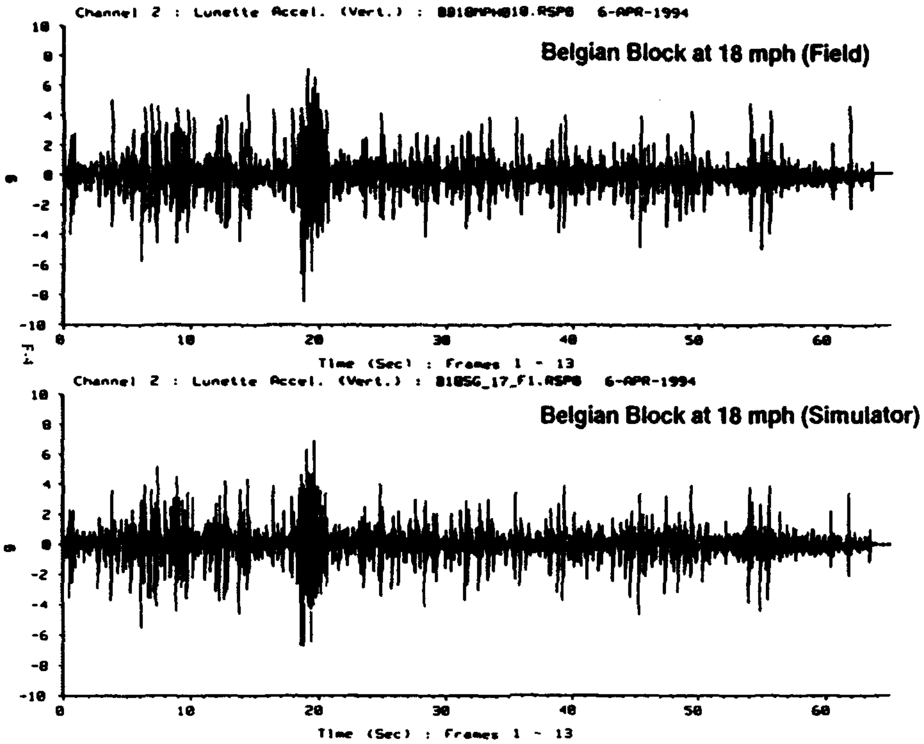

Figure 5-15. Time Comparison Between Proving Ground and Simulator (Entire Run).

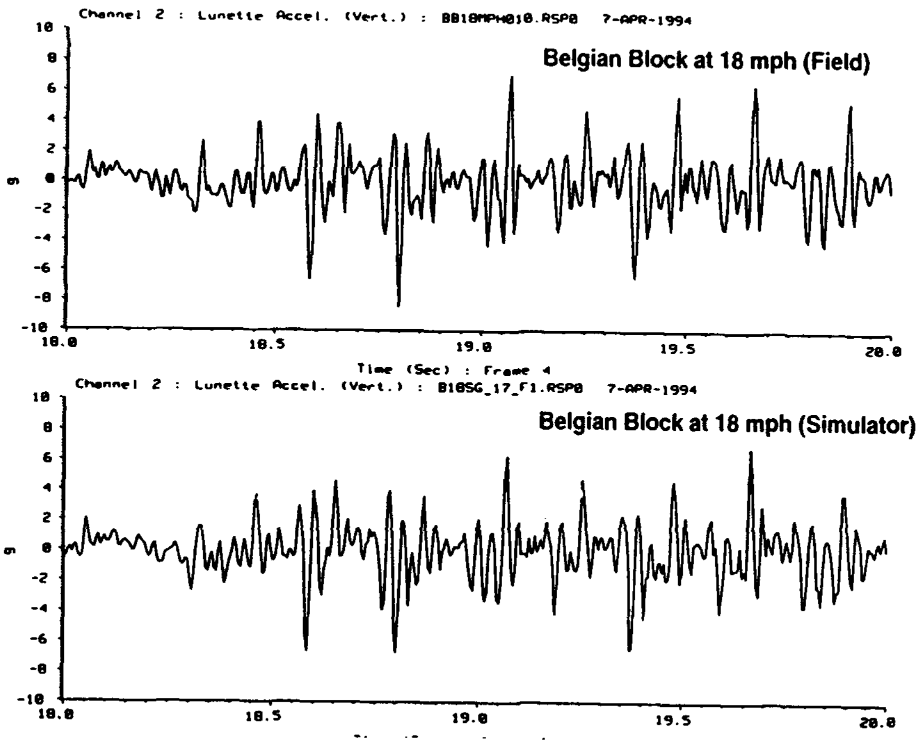

Figure 5-16. Time Comparison Between Proving Ground and Simulator (2 seconds).

5.5.2.2 *Error Analysis*. The simulator data were also compared to the proving ground data by calculating error values between corresponding channels. An error analysis was performed on the data, comparing the proving ground data to the PMBS response data. This analysis compared the two time histories via both absolute and relative errors. The maximum and average of these two error signals are reported here. Table 5-11 shows the results of this error analysis for the Belgian Block course at 18 mph. The error was calculated by removing the mean from both time histories and then taking the absolute difference to get an absolute error signal as shown in Equation 5-1.

$$\begin{aligned} E_{ABS}(t) &= |F_{NOM}(t) - S_{NOM}(t)| \\ F_{NOM}(t) &= F(t) - MEAN(F(t)) \\ S_{NOM}(t) &= S(t) - MEAN(S(t)) \end{aligned} \tag{5-1}$$

Where $F(t)$ is a time-history of proving ground data and $S(t)$ is a time-history of simulator data related to the proving ground data.

The maximum of $E_{ABS}(t)$ is the maximum absolute error (E_{ABSMAX}) and is calculated in Equation 5-2. The third column of Table 5-11 shows this value for the Belgian Block course at 18 mph.

$$E_{ABSMAX} = MAX(E_{ABS}(t)) \tag{5-2}$$

Although these values seem high, they are maximum values and as such indicate nothing about the other points in the error signal.

The average of $E_{ABS}(t)$ is the absolute average error (E_{ABSAVG}) and is reported in the fourth column of Table 5-11. $E_{ABS}(t)$ is given by,

$$E_{ABSAVG} = MEAN(E_{ABS}(t)) \tag{5-3}$$

The absolute error signal ($E_{ABS}(t)$) is then converted to relative (normalized) error ($E_{REL}(t)$) by dividing the absolute error signal by the peak-to-peak value of the reference (proving ground) signal. Relative error was calculated by the following formula,

$$\begin{aligned} E_{REL}(t) &= \frac{E_{ABS}(t)}{F_{P\text{-}P}}(100\%) \\ F_{P\text{-}P} &= MAX(F(t)) - MIN(F(t)) \end{aligned} \tag{5-4}$$

The maximum of $E_{REL}(t)$ is the maximum relative error (E_{RELMAX}) and is reported in the fifth column of Table 5-11 and is given by,

$$E_{RELMAX} = MAX(E_{REL}(t)) \tag{5-5}$$

The average value of $E_{REL}(t)$ is the average relative error (E_{RELAVG}) and is reported in the sixth column of Table 5-11 and is given by,

$$E_{RELAVG} = MEAN(E_{REL}(t)) \tag{5-6}$$

Table 5-11. Example of Error Analysis For the Belgian Block Course at 18 mph.

Channel	Unit	Max Abs (eu) *	Avg Abs (eu) *	Max Rel (%)	Avg Rel (%)
Lunette Accel. (Lat.)	g	1.52	0.206	23.88	**3.23**
Lunette Accel. (Vert.)	g	2.97	0.236	19.04	**1.51**
Lunette Accel. (Long.)	g	2.34	0.221	62.24	**5.89**
Left Spindle Accel. (Vert.)	g	5.65	0.182	46.43	**1.49**
Right Spindle Accel. (Vert.)	g	8.85	0.197	80	**1.78**
Rear Frame Accel. (Vert.)	g	1.95	0.244	39.22	**4.92**
Front Frame Accel. (Vert.)	g	2.25	0.199	33.03	**2.93**
Lunette Axial Strain (Long.)	ue	147	16.5	46.58	**5.24**
Rear Frame Accel. (Lat.)	g	3.46	0.422	79.89	**9.76**
Pitch Rate	deg/sec	24	2.36	42.1	**4.15**
Roll Rate	deg/sec	46.4	8.71	56.99	**10.68**
Yaw Rate	deg/sec	14.5	3.18	52.31	**11.45**
Left Shock Disp.	inches	2.03	0.381	55.31	**10.39**
Right Shock Disp.	inches	1.63	0.368	41.38	**9.37**

* Maximum errors are relatively high because this value represents only one pair of points of thousands in the entire compared time history.

The average error is the best indication of the accuracy of the entire run because it represents the whole time history rather than one point (of thousands) of the time history, as the maximum error value does. Relative error, although it does rely on the maximum and minimum of the proving ground data, is better at normalizing the error so that the errors on mild and severe terrains can be compared accurately.

For a more comprehensive analysis of the error, cumulative histograms of the relative error signal show the total amount of the error signal below a given error level. This gives an indication of how the error is distributed and illustrates how often the error is within an acceptable tolerance. Figure 5-17 is a cumulative error histogram for the Belgian Block course at 18 mph. There are six of these histograms contained in this one graph (five RPC™ channels and longitudinal lunette acceleration). The X-axis represents an error level and the Y-axis represents the percentage of the time that the error is less than or equal to the given error level. For example, in Figure 5-17, the three vertical channels have less than 5 percent error 92 percent of the time. The further a given curve is to the left the better the correlation is for that channel. So in Figure 5-17, the three vertical channels correlate better than the other three. The longitudinal lunette acceleration correlates the least of these channels because it is not a control channel. A complete set of similar error analyses is presented for each of the other runs in Appendix G. The average relative error for all 14 channels of all of the runs is 5.9 percent. The average relative error for the RPC™ channels is 3.1 percent.

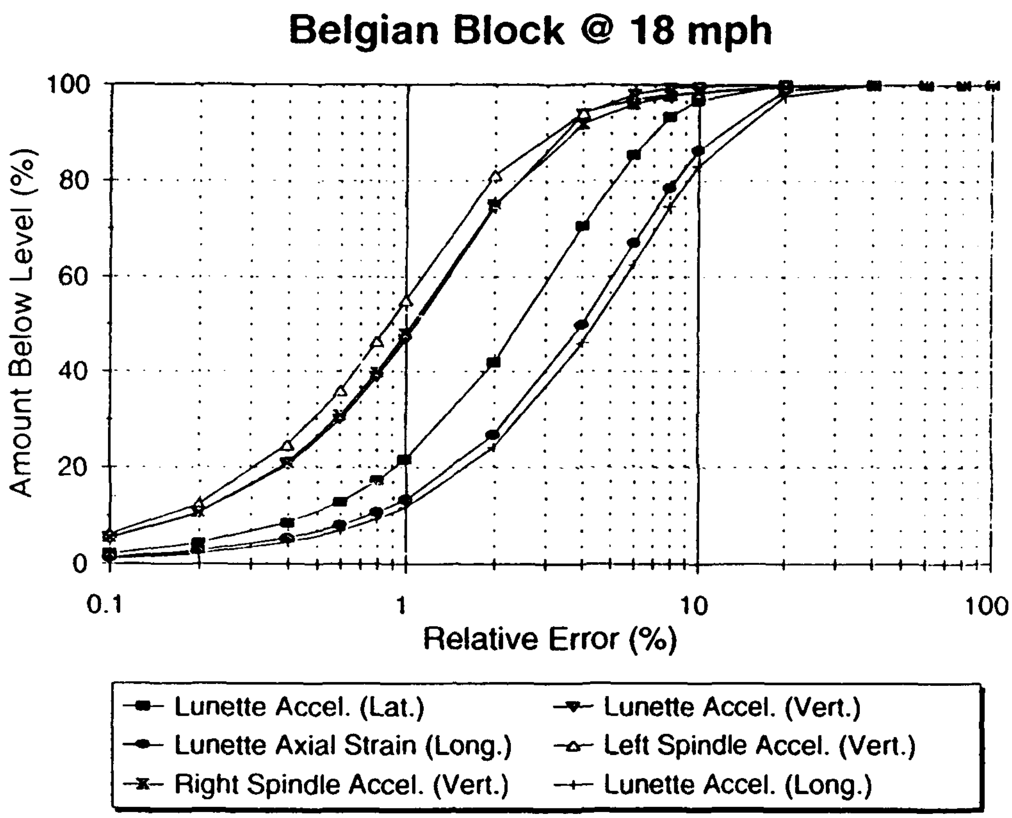

Figure 5-17. Cumulative Error Histogram of Relative Error of the Simulator Response to Proving Ground Data.

5.5.3 Comparisons in the frequency domain

Although time domain comparisons are useful, comparisons in the frequency domain add two benefits: (1) they allow one to see the particular frequencies where the signals differ and thus allow the engineer to better understand the causes of these differences and (2) they allow the comparison of signals which have no relation in time. The following comparisons are made in the frequency domain:

- Proving ground vs. PMBS using proving ground inputs
- Proving ground vs. PMBS using DADS inputs
- PMBS (proving ground input) vs. Fixed Lunette.

All of the plots presented in this section are power spectral densities (PSDs) calculated by averaging many five-second PSDs. This yields a frequency resolution of 0.2 Hz. Since the comparisons are made using PSDs there is no phase information available for comparison and the amplitude units are of the form EU^2/Hz where EU represents the engineering units in which the time domain signal was measured.

5.5.3.1 *Proving ground compared to PMBS with proving ground data as input.* The proving ground data are distinguished from the simulator data in this section by the F (proving ground) and S (simulator) markings. Figure 5-18 contains a comparison of the vertical lunette acceleration data from the proving ground and simulator on the Belgian Block course at 18 mph. This channel correlates better than any of the other RPC™ channels as can be seen in the fourth column of Table 5-11 (1.5 percent average error). There is excellent correlation out to 40 Hz which is the control bandwidth for this test. The proving ground data, however, have components beyond 40 Hz. Any correlation beyond the control bandwidth is a result of the al response of the trailer/simulator system. The proving ground and simulator PSDs do not ay past 40 Hz but they remain close to each other all the way to 82 Hz. The PSDs would match even closer if the simulator response did not dip at 56 and 78 Hz.

Figure 5-19 contains the comparison of the lunette axial strain data from the proving ground and simulator. This signal correlates the least of all the control channels, but, the PSD clearly shows that the simulator is reproducing the correct strains within the bandwidth of control. In the uncontrolled portion of the spectrum (past 40 Hz) the strain levels are considerably higher in the simulator data than in the proving ground data. This indicates that the PMBS is overexerting the trailer in this frequency band. This, however, represents considerable improvement over acceleration control represented in Figure 5-6. There are several possible causes of the overshoot seen in Figure 5-19. Three possible causes are:

(1) The mass of the PMBS linkage reacts inertially against the natural vibration of the trailer. Since the drive command has very little energy in the uncontrolled regions, the linkage is essentially held rigid at these frequencies, which represents an unnatural constraint.
(2) A resonance was found in the vertical channel at 43 Hz. The partial coherences in Figure 5-11 indicate that, past 40 Hz, the vertical input channel has more influence over the strain channel than does the longitudinal input. This means that a resonance at 43 Hz in the vertical actuator will affect the strain channel and will produce error at 43 Hz.
(3) Also, less than optimum transducer choice/location for the proving ground test may have caused some problems. Other strain channels, if recorded, would have offered additional comparisons.

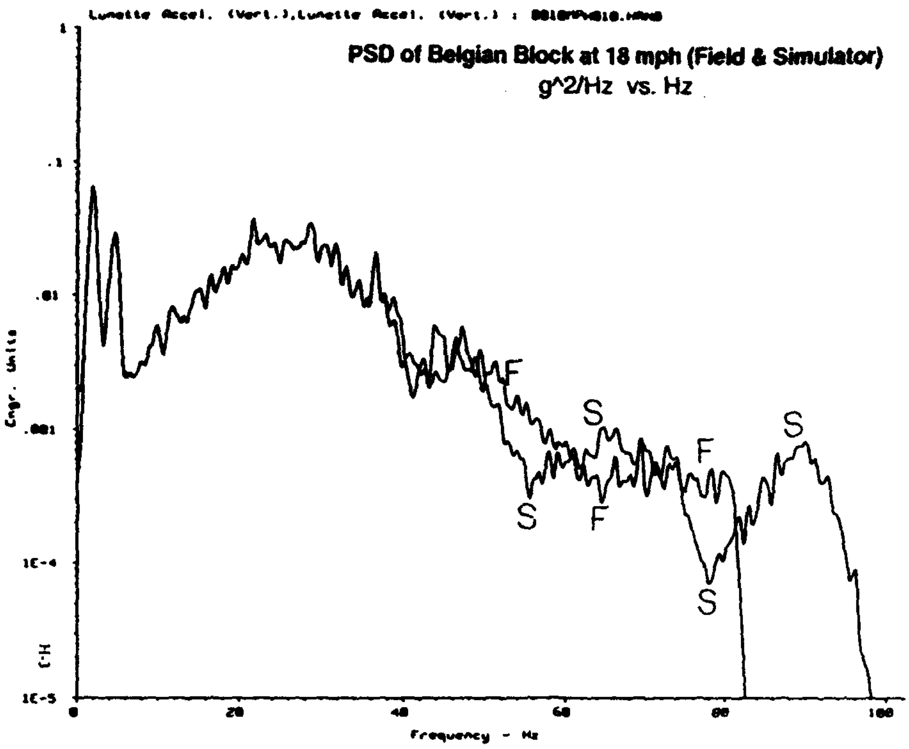

Figure 5-18. Frequency Domain Comparison of Vertical Lunette Acceleration.

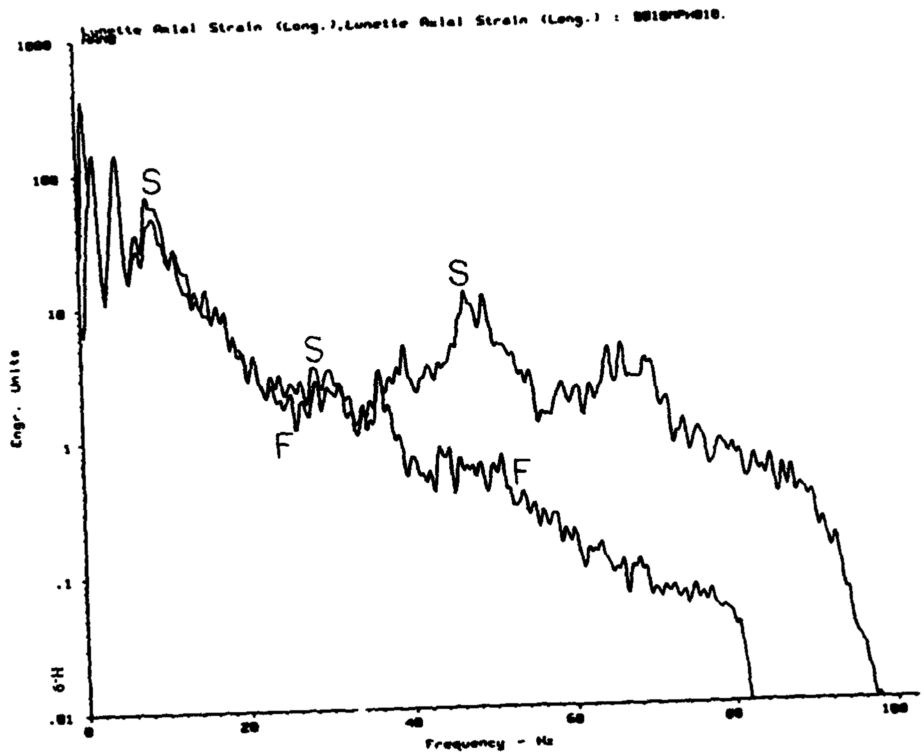

Figure 5-19. Frequency Domain Comparison of Longitudinal Lunette Strain.

The previous two comparisons of vertical acceleration and longitudinal strain were of RPC™ channels and matched within the controlled bandwidth. The correlation transducers are those which are not controlled. Figure 5-20 shows a comparison of the front frame accelerometer data from the proving ground and the simulator. The two channels do not exactly overlay but for the most part they contain approximately the same energy level. Throughout the plotted frequency range the simulator data always seem to have less energy than the proving ground data. This channel does not correlate as well because it is not a control channel. If the simulator were able to constrain the trailer in the same manner as it is at the proving ground, then these two channels would match better. Another reason that these channels differ is that, in the lab, the trailer landing gear was removed because it rattled around and generated a lot of noise causing spurious accelerations in the control channels. Appendix H contains a complete comparison of the data in frequency domain.

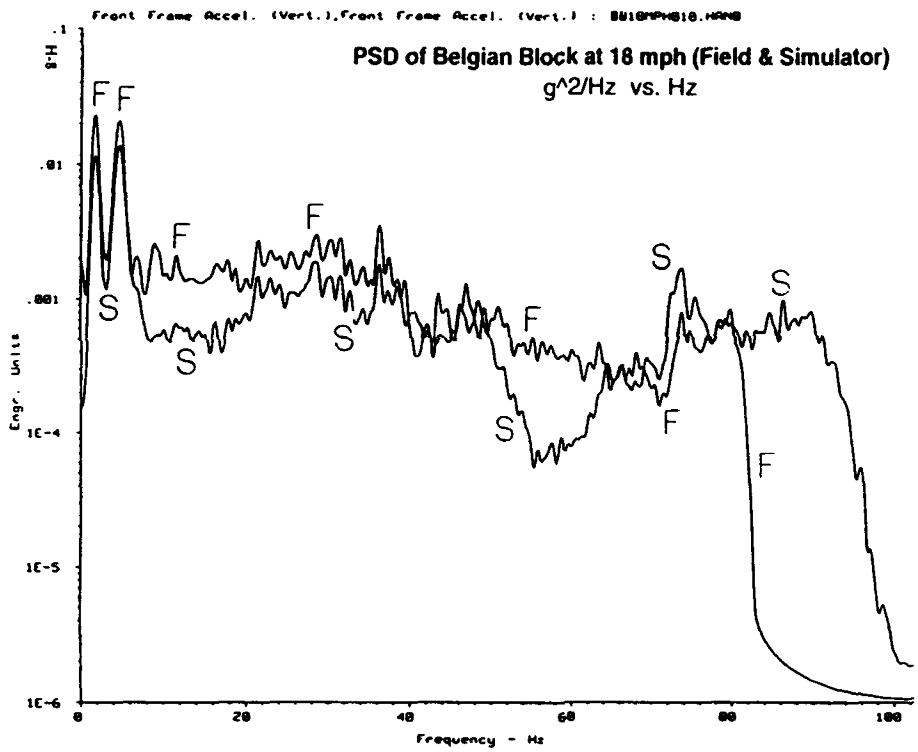

Figure 5-20. Frequency Domain Comparison of Vertical Front Frame Acceleration.

5.5.3.2 *Proving ground compared to PMBS with DADS data as input.* The ability to accurately test a trailer using DADS data as input directly depends on the accuracy of the DADS model. This section compares, in the frequency domain, the proving ground data to the PMBS response using the data from the rigid body DADS model as input. Figures 5-21 through 5-23 display plots of the RPC™ control channels from the proving ground and DADS. The Belgian Block course could not be run at 18 mph because it was too severe (especially in the lower, high displacement frequencies); 15 mph was the highest speed safely simulated and is used for this comparison. The plots indicate that the DADS model produces less energy than the proving ground in the higher frequencies when used as input to the PMBS. Figure 5-21 shows that DADS produces more strain in most of the frequency range of the plot. This is because acceleration was the controlling parameter in the longitudinal direction and, as mentioned in section 5.4.1 this tends to overexert the longitudinal strain.

Acceleration was used as a control parameter in the longitudinal direction for this portion of the test because there were no strain data available from the DADS model. Although strain is recorded from the simulator, the DADS model does not output strain. Therefore acceleration was used as the control parameter for the longitudinal direction.

Figures 5-22 and 5-23 illustrate the comparison of two acceleration data channels. Figure 5-22 represents the vertical lunette acceleration, which is a control channel. As can be seen, the simulator is inputing less energy than the proving ground run did. Also, in Figure 5-23, the proving ground signal contains more energy in most of the region of interest. The simulator response when controlled to DADS is mild in the high-frequency regions because the DADS model, which produced the controlling parameters, is a rigid-body dynamics model and as such it does not produce the high-frequency components that are present at the proving ground.

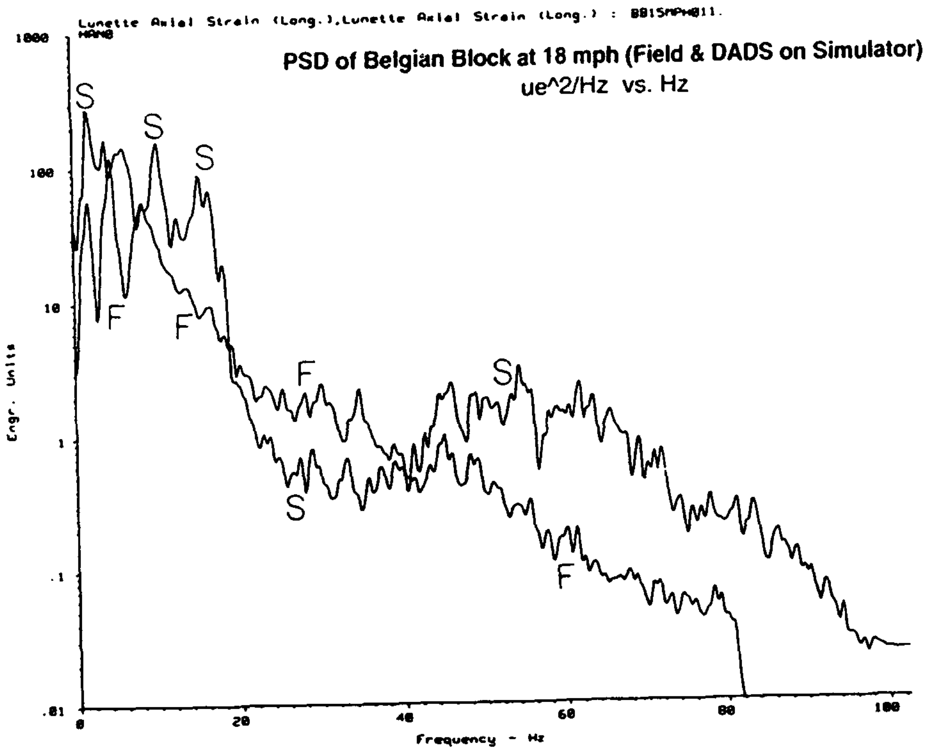

Figure 5-21. Frequency Domain Comparison Longitudinal Lunette Axial Strain

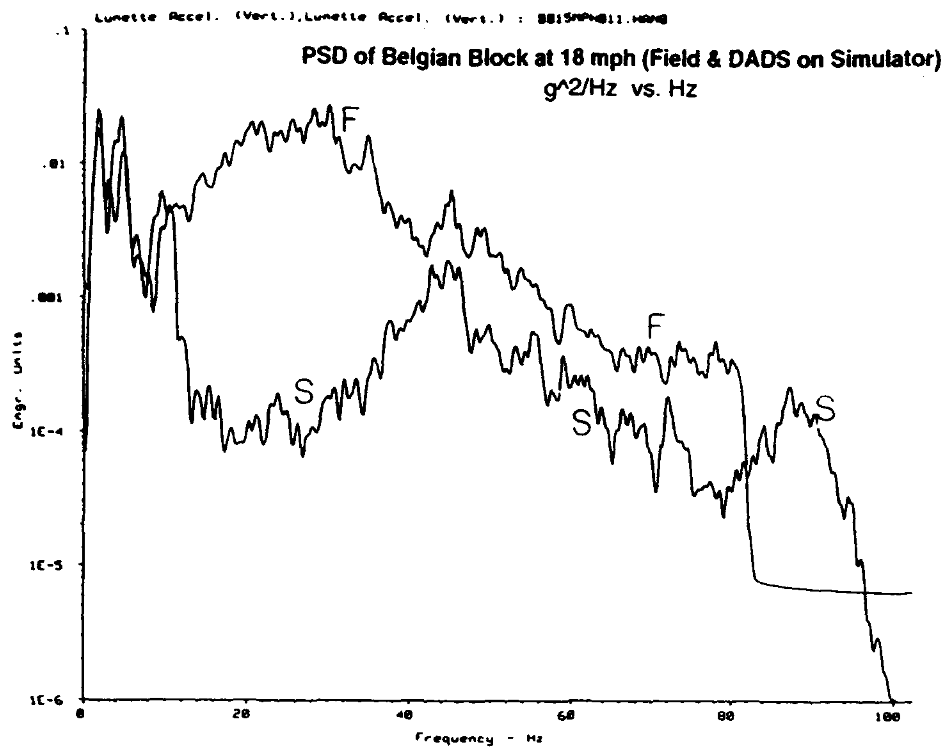

Figure 5-22. Frequency Domain Comparison Vertical Lunette Acceleration.

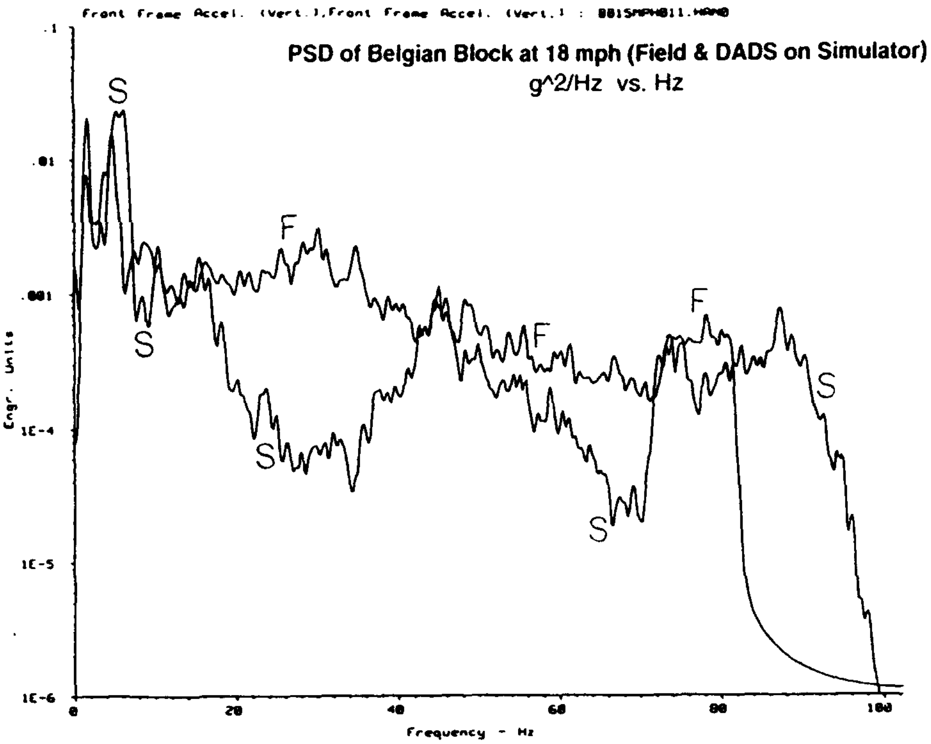

Figure 5-23. Frequency Domain Comparison Vertical Front Frame Acceleration.

5.5.3.3 *PMBS compared to Fixed Lunette Simulator data.* The PMBS combined with the RPC™ III software represents major improvements in the accuracy of trailer simulation over the old fixed-lunette test method. This section compares the PMBS results to the fixed-lunette test results. Figures 5-24 and 5-25 represent two channels which can be accurately compared from the Perryman 1 course at 20 mph. Figure 5-24 contains a comparison of the longitudinal axial strain data at the lunette from the proving ground and from the fixed-lunette simulator. As can be seen, the fixed-lunette method does not even come close to reproducing the correct strain levels at this important trailer input. However, Figure 5-25 depicts the comparison of the front frame acceleration data. Here the channels correlate better in the high frequencies, but they do not correlate in the lower frequencies. This channel obviously gets its energy from the vertical input to the tires. This demonstrates that the fixed-lunette simulation method does not accurately reproduce the vertical frame accelerations, neither does it produce the correct energy levels in the longitudinal direction, thus the need for the PMBS.

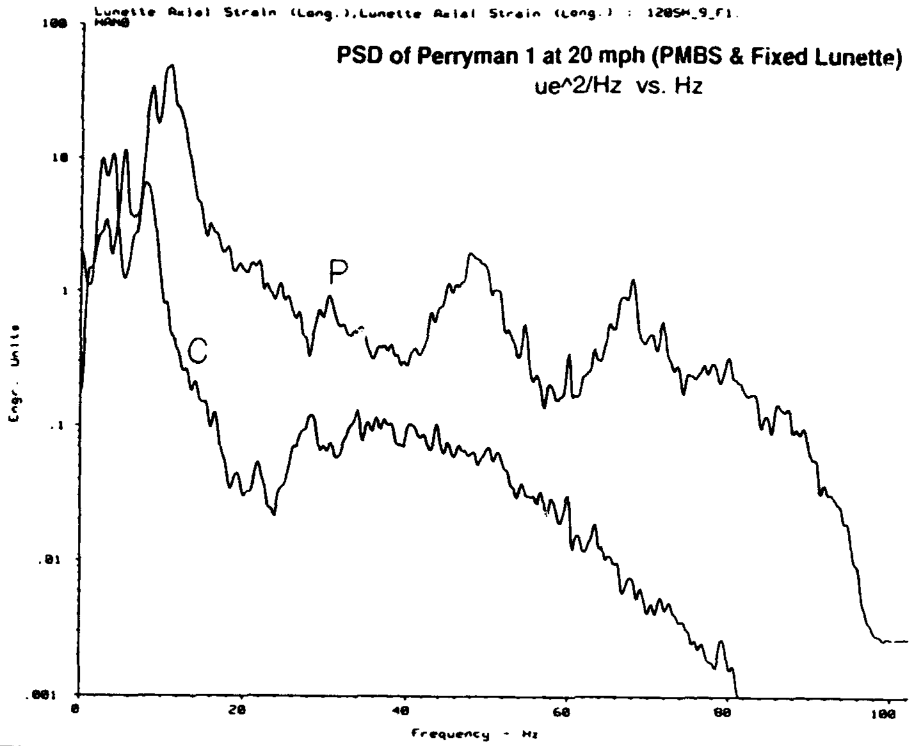

Figure 5-24. Frequency Domain Comparison of Longitudinal Lunette Axial Strain

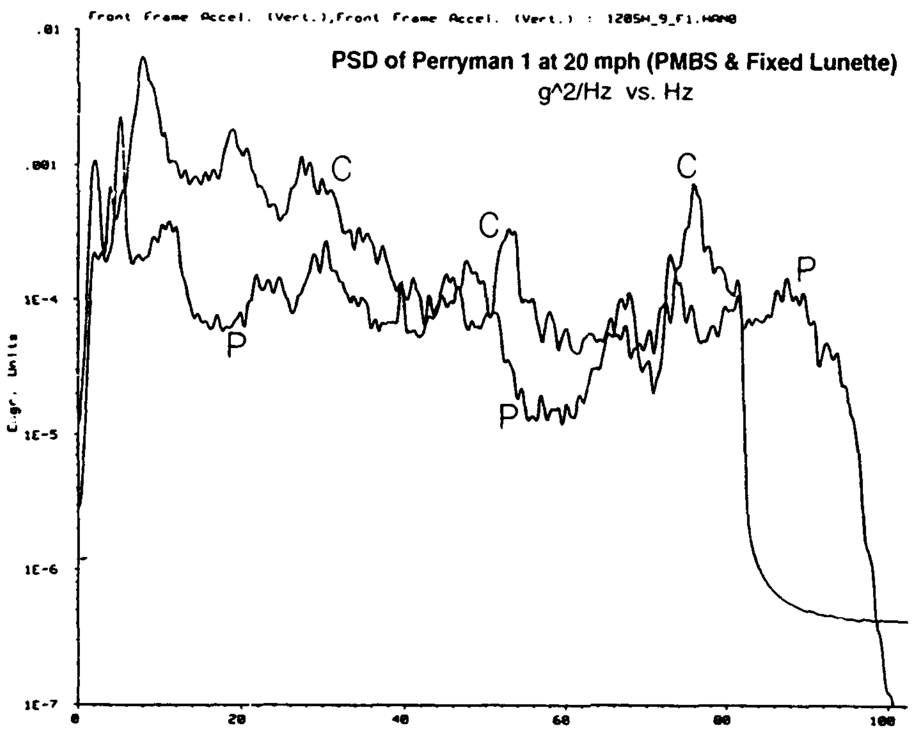

Figure 5-25. Frequency Domain Comparison of Vertical Front Frame Accel.

Additional comparisons in the frequency domain can be found in Appendix H.

5.5.4 Orthogonal Channel Comparisons

All of the comparisons thus far have been of RPC™ and correlation channels which are expected to correlate to a certain degree. This section, however, compares the lateral and longitudinal spindle accelerations which are not controlled by the simulator. Figures 5-26 and 5-27 show the comparison of the lateral and longitudinal spindle accelerations from the Belgian Block course at 18 mph for 2 seconds (18 to 20 sec.). By observing the time histories, it can be seen that they do not correlate exactly. There is, however, some correlation in the signal levels. Since the time histories do not exactly correlate, a comparison in the frequency domain is required. Figures 5-28 and 5-29 depict frequency domain comparisons of the same two data channels. These plots further indicate that the lateral and longitudinal accelerations are reproduced with approximately the correct energy levels in all frequency bands, even beyond the bandwidth of control (< 60 Hz). This indicates that the PMBS approximately reproduces the correct acceleration levels in the uncontrolled directions through the natural response of the trailer tires on the simulator.

Although the lateral and longitudinal spindle accelerations have matched in the frequency domain fairly well, this does not verify that the correct damage is being reproduced in these directions. It is noted that the automotive industry usually uses strain control in the lateral and longitudinal directions, because they are not necessarily inertially reacted like the vertical spindle channel. (i.e., they do not move much when a force is applied.) Since the vertical channel is the one by which the suspension is tested, it is most important that this channel be reproduced correctly. The lateral and longitudinal channels become significant when the trailer corners, brakes, or traverses large bumps.

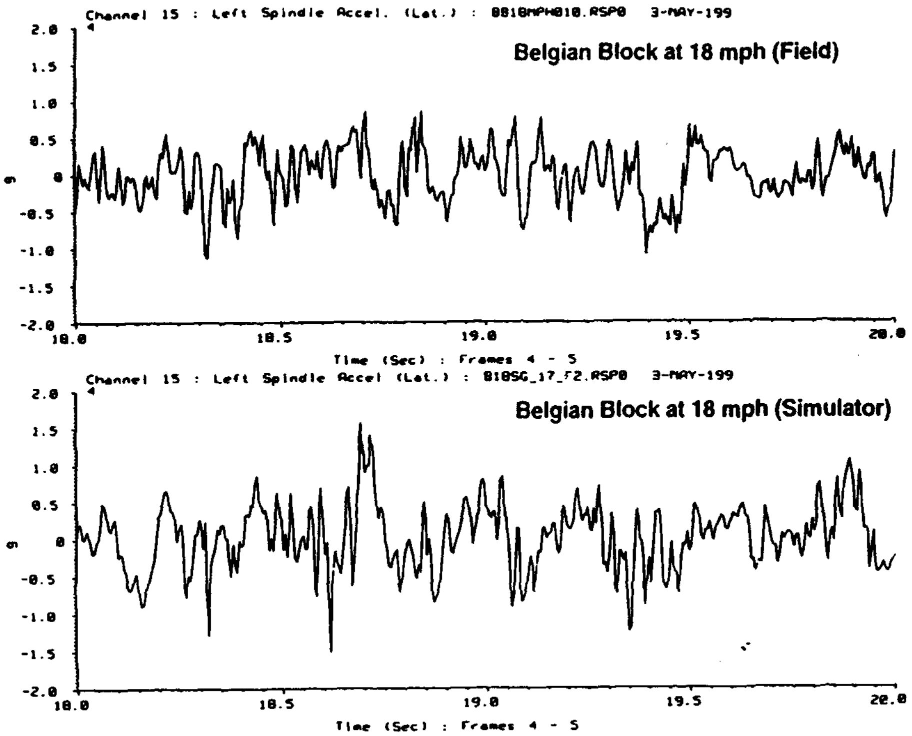

Figure 5-26. Time-Domain Comparison of Lateral Spindle Acceleration.

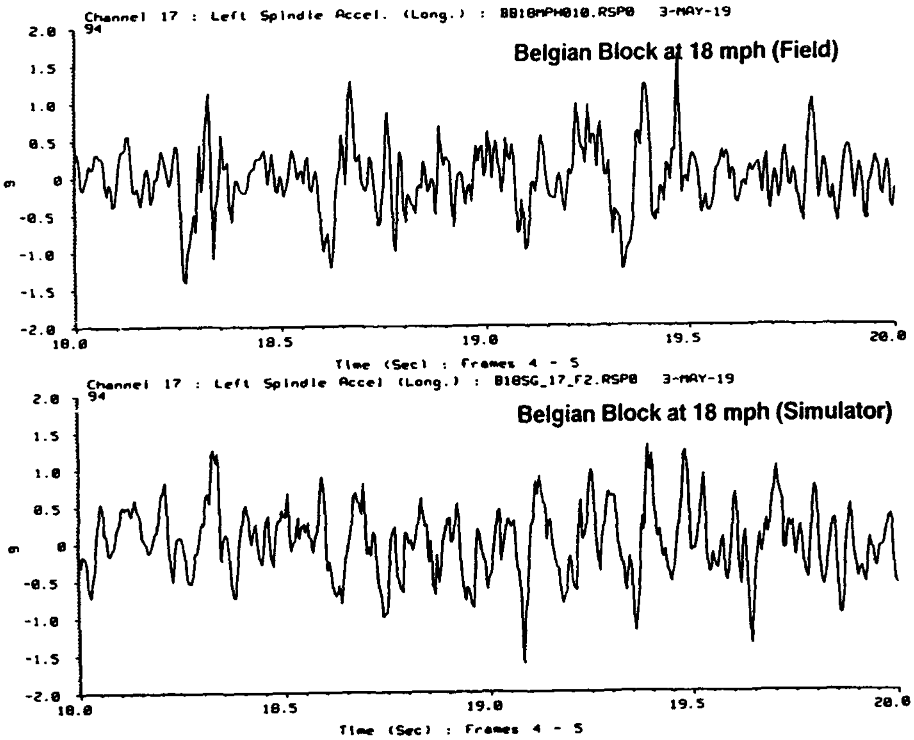

Figure 5-27. Time-Domain Comparison of Longitudinal Spindle Acceleration.

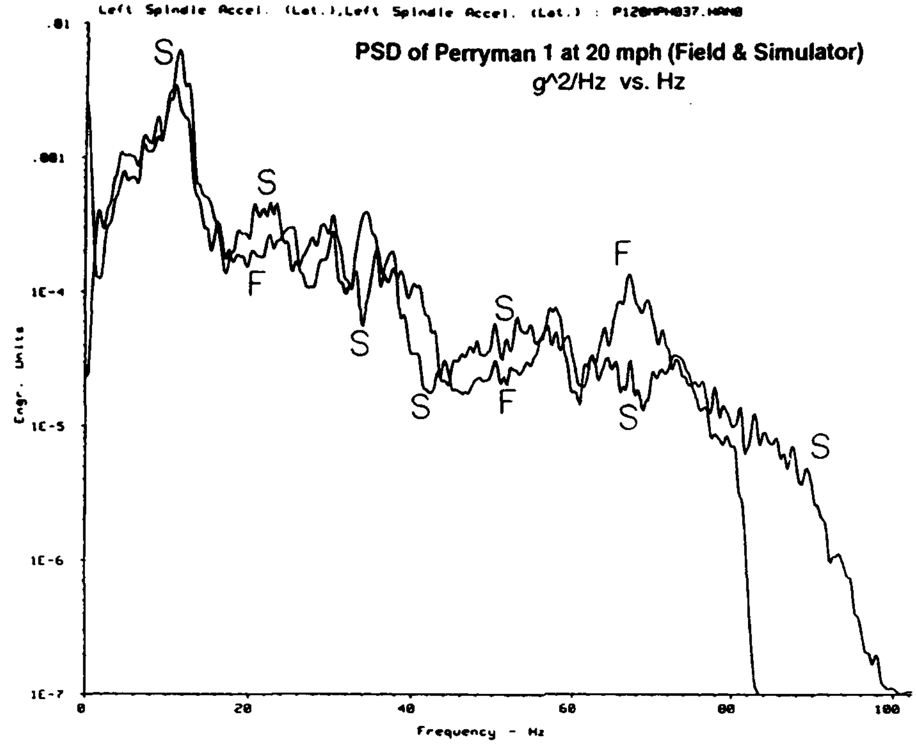

Figure 5-28. Frequency-Domain Comparison of Lateral Spindle Acceleration.

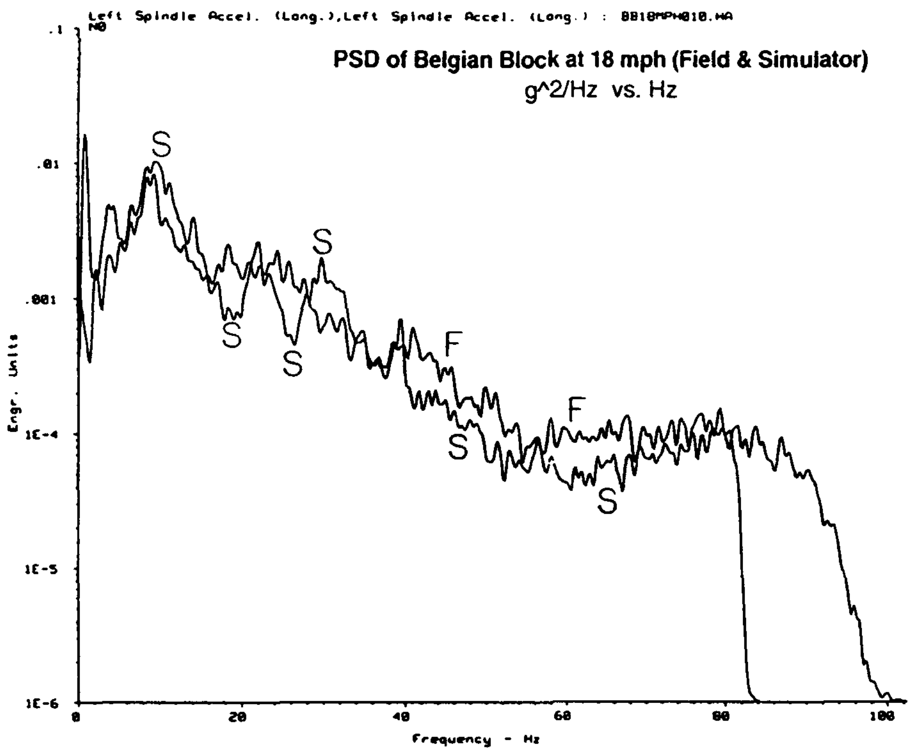

Figure 5-29. Frequency-Domain Comparison of Longitudinal Spindle Acceleration.

5.5.5 Histogram Comparisons of Suspension Travel

Although spindle acceleration control was used for the vertical tire actuators, and the simulator accelerations matched the proving ground accelerations out to 60 Hz, acceleration is not directly related to damage in the suspension system. A better parameter for comparing damage is suspension displacement. This section compares the suspension travel data from the proving ground vs. that from the simulator. There are, however, some inherent discrepancies between the proving ground measurement and the simulator measurement due to transducer type and location. At the proving ground, the suspension travel was measured with linear potentiometers mounted in-line with the shock absorbers. In the lab it was measured by running string potentiometers from the wheel spindles up to the body of the trailer because linear potentiometers were available. One inherent discrepancy is that at the proving ground displacement was measured closer to the center of the axle. This means that the proving ground values should be smaller and the proving ground histograms should be slightly narrower than the lab histograms. Another discrepancy is that the string potentiometer in the lab is influenced by the side-to-side motions of the axle, whereas proving ground potentiometers were not.

The means of comparison in this section is the histogram. All compared histograms are calculated with the same number of points and a bin size of 0.125 inch. Positive values represent extension of the suspension while negative values represent compression of the suspension.

5.5.5.1 *Proving ground compared to PMBS using proving ground data as input.* Figures 5-30 and 5-31 present the histograms of the left suspension travel from the Belgian Block course at 18 mph. Figure 5-30 is from the proving ground data and Figure 5-31 is from the PMBS using proving ground data as input. Both figures have the same horizontal axis but they have different vertical scales. Figure 5-30 is on a scale of approximately 1600 counts and Figure 5-31 is on a scale of 2400 counts. The large vertical scale for the proving ground data is caused by the large component at zero. This is caused by the zeros which are appended to the end of a time history of data to fill the last five-second frame. The areas that should be of interest are the regions below -1.0 inch. These represent larger excursions into the trailer which cause most of the damage.

5.5.5.2 *Proving ground compared to PMBS with DADS data as input.* Figures 5-32 and 5-33 show the histograms of the left suspension travel from the Belgian Block course at 15 mph. Figure 5-32 represents the proving ground data and Figure 5-33 is from the PMBS using DADS model data as input. Both figures have the same horizontal scales but they have different vertical scales. Figure 5-32 is on a scale of approximately 2400 counts and Figure 5-33 is on a scale of 2600 counts. These histograms are not as similar as the previous two were. The PMBS data has much more content below -1.0 inch which represents compression of the spring by more than 1.0 inch. This means that the PMBS using DADS data as input overtests the trailer suspension for this course. This further supports the conclusion that the specimens are overtested when using DADS data as input.

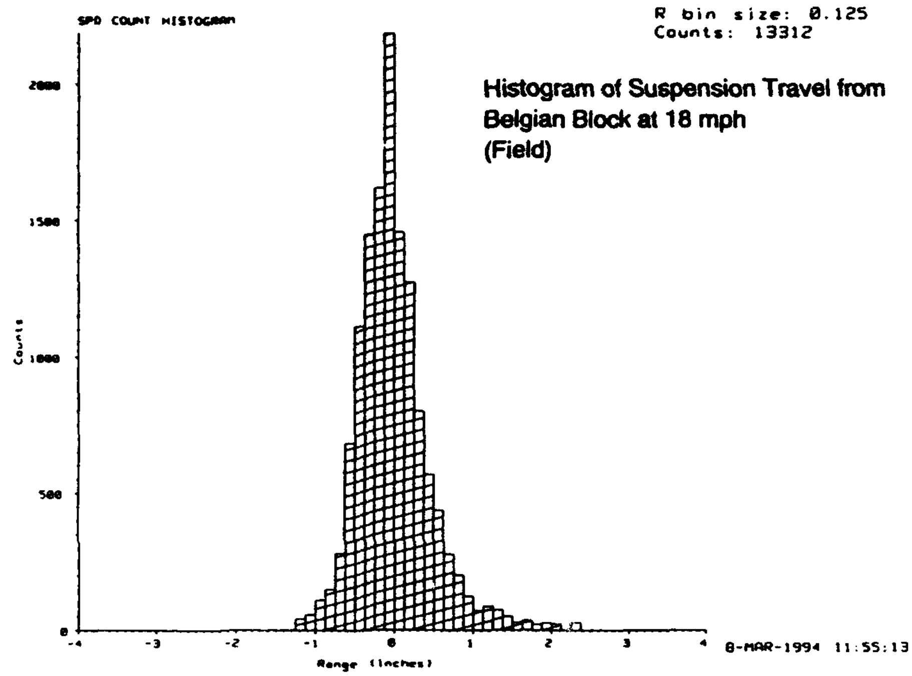

Figure 5-30. Histogram of Suspension Travel (Belgian Block @ 18 mph from the proving ground)

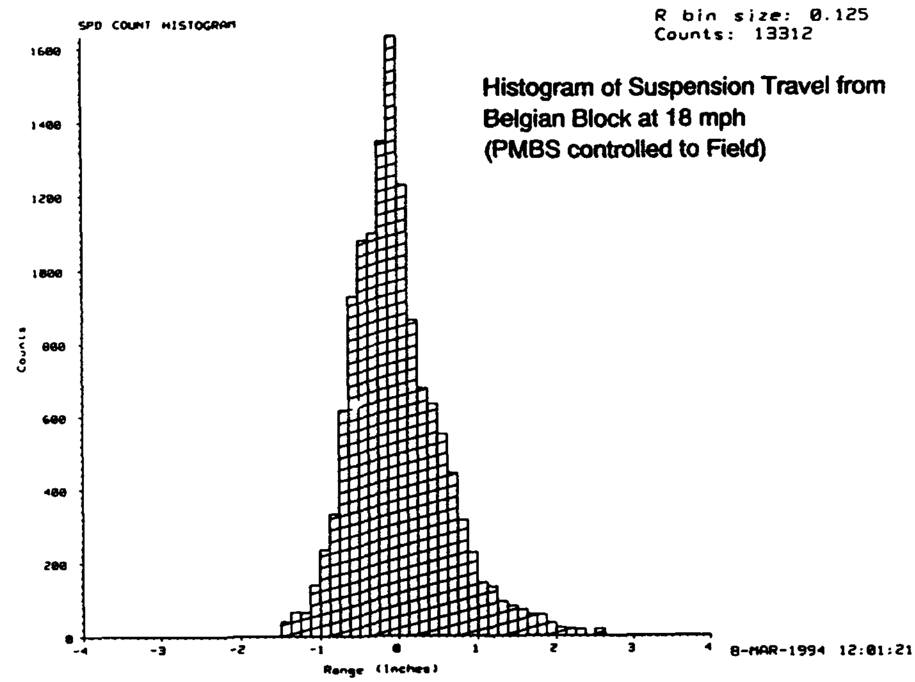

Figure 5-31. Histogram of Suspension Travel (Belgian Block @ 18 mph from PMBS)

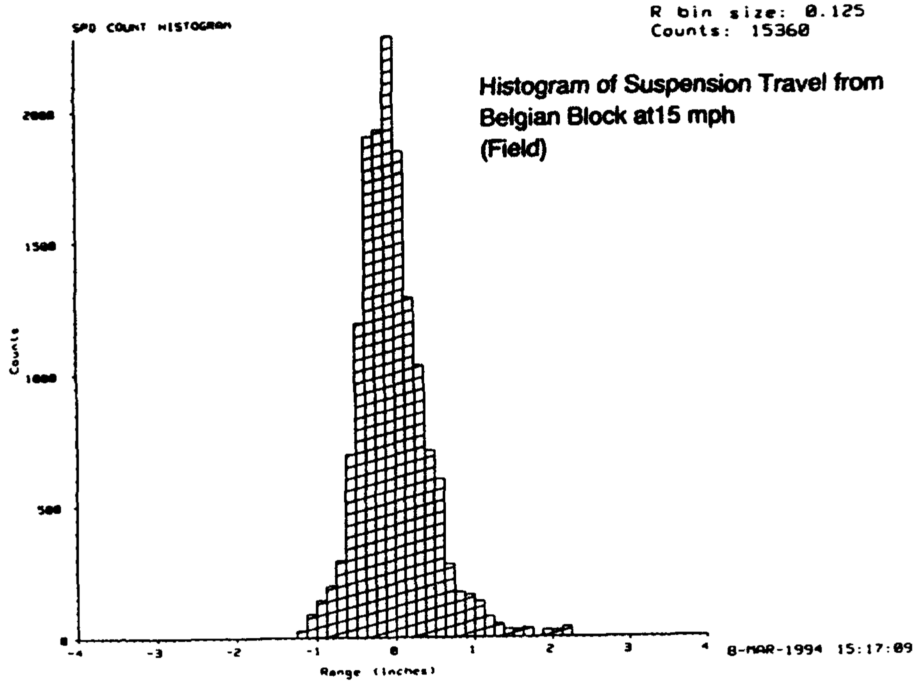

Figure 5-32. Histogram of Suspension Travel (Belgian Block @ 15 mph from the proving ground)

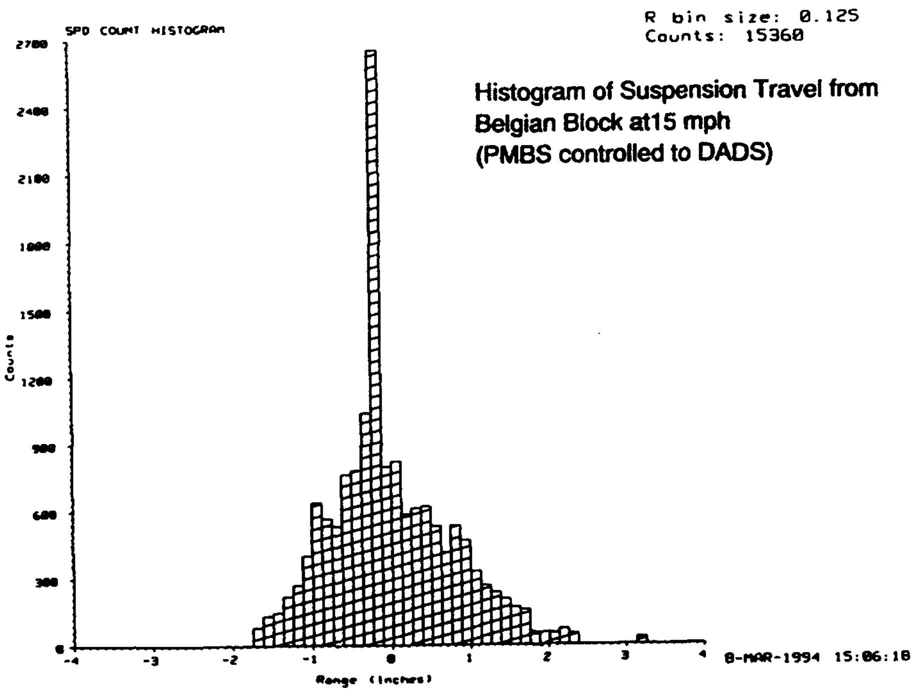

Figure 5-33. Histogram of Suspension Travel (Belgian Block @ 15 mph from PMBS-DADS)

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